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The Resources Agency

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Evaluation of Ground Water Resources Sonoma County Volume 3: Petaluma Valley

Department of Water Resources
in cooperation with the Sonoma County Water Agency

Bulletin 118-4
June 1982



ON THE COVER: Wind power pumps ground water from these wells at the base of Meacham Hill for agricultural use. Many private domestic and agricultural water wells provide ground water for use in rural areas of Petaluma Valley

**Department of Water Resources
In cooperation with the
Sonoma County Water Agency**

Bulletin 118-4

**Evaluation of
Ground Water
Resources:
Sonoma County**

**Volume 3:
Petaluma Valley**

June 1982

Huey D. Johnson
Secretary for Resources

Edmund G. Brown Jr.
Governor

Ronald B. Robie
Director

**The Resources
Agency**

**State of
California**

**Department of
Water Resources**

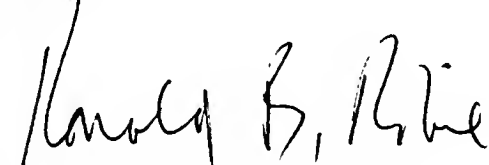
FOREWORD

Ground water plays an important role in Sonoma County. As the population of this North Bay county has increased over the last 30 years, the use of ground water has likewise increased. Currently, over 15,000 wells have been identified in the county. These wells are used for domestic and agricultural purposes in rural areas and for municipal and industrial purposes in urban areas.

The Sonoma County Water Agency (SCWA) requested the California Department of Water Resources (DWR) to join a cooperative study to estimate the volume of ground water in storage and the recharge potential in the Santa Rosa Plain, Petaluma Valley, Sonoma Valley, and Alexander Valley and Healdsburg area. The study examined alternative ways the ground water resources of the county may be used conjunctively with the Russian River and other surface water sources.

The results of the study are presented in four volumes. This report is Volume 3, and describes ground water conditions in the Petaluma Valley. Volume 2 deals with the Santa Rosa Plain, Volume 4 with the Sonoma Valley, and Volume 5 with the Alexander Valley and Healdsburg area. The present study was designed to augment the earlier countywide investigation of geology and hydrology conducted jointly by the Sonoma County Planning Department and DWR. Results of the earlier investigation were published as DWR Bulletin 118-4, Volume 1 (Ford, 1975).

This report on the Petaluma Valley includes an evaluation of geologic and hydrologic characteristics of the ground water basin, an evaluation of the volume of usable ground water in the basin and the volume that can reasonably be extracted, possible changes in water quality resulting from pumping of ground water, an evaluation of the interconnection of ground and surface waters, and the potential for artificial recharge of the ground water basin.



Ronald B. Robie, Director
Department of Water Resources
The Resources Agency
State of California

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PLATE (in separate pocket)

1. Geology of Petaluma Valley

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CENTRAL DISTRICT

Wayne MacRostie District Chief
Kenneth Woodward Chief, Planning Office
Robert L. McDonell Chief, Special Studies Branch

This Bulletin was prepared
under the supervision of

Louis R. Mitchell Senior Engineer, Water Resources
Carl J. Hauge Senior Engineering Geologist
Robert S. Ford Supervising Engineering Geologist

by

Charlene M. Herbst Assistant Engineering Geologist

Assistance was provided by

Leslie Cole Student Assistant
Grace Haggerty Student Assistant
Larry Hilbers Engineering Student Assistant
Tom Hilinski Student Assistant
Karen Osgood Student Assistant
Eric Senter Student Assistant
Howard Snyder Student Assistant
Carol Thompson Student Assistant
Woodfin P. Riley Water Resources Technician I
Harry Inouye Senior Delineator
Vera Doherty Editorial Technician
Cathy Wilson Word Processing Technician
Betty Swatsenbarg Geologic Aid
Judy Van Dyke Stenographer

Appreciation is given for information and suggestions
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Garniss H. Curtis, Ph.D University of California, Berkeley
Kenneth F. Fox, Jr., Ph.D U. S. Geological Survey
Geoffrey D. Woodard, Ph.D Sonoma State University

SONOMA COUNTY WATER AGENCY

Directors

Bob Adams Ernie Carpenter Nick Esposti
Helen Putnam Helen Rudee

Robert F. Beach
General Manager

Carl R. Jackson
Assistant Chief Engineer

Contributing Technical Assistance by:

Willard R. Stillman, Civil Engineer IV
Robert J. Cortelyou, Civil Engineer III
John Kunselman, Civil Engineer III*
Cliff McDivitt, Engineering Technician III
Ken Screechfield, Engineering Technician III
Roger Swenson, Engineering Technician III

*Resigned

State of California
Department of Water Resources
CALIFORNIA WATER COMMISSION

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Tom Y. Fujimoto
Assistant Executive Officer

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CONVERSION FACTORS

Quantity	To Convert from Metric Unit	To Customary Unit	Multiply Metric Unit By	To Convert to Metric Unit Multiply Customary Unit By
Length	millimetres (mm)	inches (in)	0.03937	25.4
	centimetres (cm) for snow depth	inches (in)	0.3937	2.54
	metres (m)	feet (ft)	3.2808	0.3048
	kilometres (km)	miles (mi)	0.62139	1.6093
Area	square millimetres (mm ²)	square inches (in ²)	0.00155	645.16
	square metres (m ²)	square feet (ft ²)	10.764	0.092903
	hectares (ha)	acres (ac)	2.4710	0.40469
	square kilometres (km ²)	square miles (mi ²)	0.3861	2.590
Volume	litres (L)	gallons (gal)	0.26417	3.7854
	megalitres	million gallons (10 ⁶ gal)	0.26417	3.7854
	cubic metres (m ³)	cubic feet (ft ³)	35.315	0.028317
	cubic metres (m ³)	cubic yards (yd ³)	1.308	0.76455
	cubic dekametres (dam ³)	acre-feet (ac-ft)	0.8107	1.2335
Flow	cubic metres per second (m ³ /s)	cubic feet per second (ft ³ /s)	35.315	0.028317
	litres per minute (L/min)	gallons per minute (gal/min)	0.26417	3.7854
	litres per day (L/day)	gallons per day (gal/day)	0.26417	3.7854
	megalitres per day (ML/day)	million gallons per day (mgd)	0.26417	3.7854
	cubic dekametres per day (dam ³ /day)	acre-feet per day (ac-ft/day)	0.8107	1.2335
Mass	kilograms (kg)	pounds (lb)	2.2046	0.45359
	megagrams (Mg)	tons (short, 2,000 lb)	1.1023	0.90718
Velocity	metres per second (m/s)	feet per second (ft/s)	3.2808	0.3048
Power	kilowatts (kW)	horsepower (hp)	1.3405	0.746
Pressure	kilopascals (kPa)	pounds per square inch (psi)	0.14505	6.8948
	kilopascals (kPa)	feet head of water	0.33456	2.989
Specific Capacity	litres per minute per metre drawdown	gallons per minute per foot drawdown	0.08052	12.419
Concentration	milligrams per litre (mg/L)	parts per million (ppm)	1.0	1.0
Electrical Conductivity	microsiemens per centimetre (uS/cm)	micromhos per centimetre	1.0	1.0
Temperature	degrees Celsius (°C)	degrees Fahrenheit (°F)	(1.8 × °C) + 32	(°F - 32)/1.8

CHAPTER 1. INTRODUCTION

The Petaluma Valley (Figures 1 and 2) is one of the most rapidly urbanizing regions in the North Bay area and, as the population has increased, so has the demand for water. Ground water, i.e., water stored underground in the spaces between grains of sand and gravel and in cracks in consolidated rocks, plays an important role in meeting this demand.

Today, the valley's largest city, Petaluma, meets 15 percent of its water demand with ground water. During 1980, 1 100 cubic dekametres (dam³) (900 acre-feet (ac-ft)) of ground water was pumped from the Petaluma municipal wells.

The increase in population in the rural areas of the valley affects local ground water supplies even more significantly. The population of the unincorporated upland area north and west of Petaluma has increased 28 percent over the last 10 years -- from 5,840 to 7,460; the number of housing units has increased 44 percent -- from 1,810 to 2,610 (Criss, 1981). This has resulted in an additional 800 wells and 800 septic tanks in this 5 830-hectare (14,400-acre) area.

To present some ideas on the conjunctive use of ground and surface water, this study evaluates the hydrologic characteristics of this rapidly growing area and the effects of increased use on the ground water resource.

The Petaluma Valley was numbered 2-1 in California Department of Water Resources (DWR) Bulletin 118 (California Department of Water Resources, 1975). The valley is now included with other contiguous

ground water reservoirs in the county in the Sonoma County Basin (Peters, 1980).*

Location of Study Area

The study area comprises 24 400 hectares (60,000 acres)** extending from Penngrove south to the Marin County line and San Pablo Bay (Figure 2). It includes the Two Rock area to the west, and extends east to the crest of the Sonoma Mountains, which separate the Petaluma and Sonoma Valleys. This area includes most of the watershed of the Petaluma River.

Method of Investigation

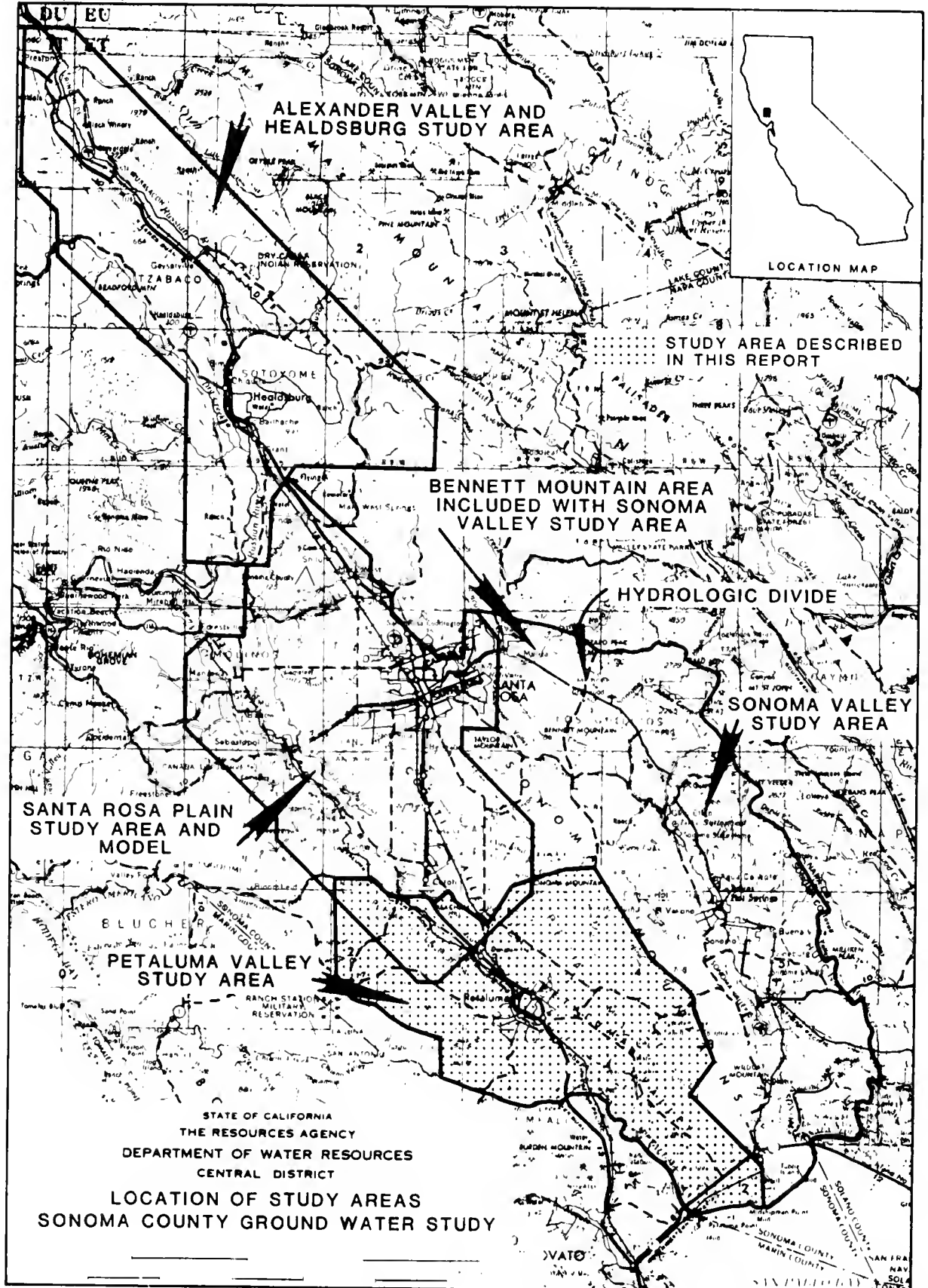
To simplify compilation and evaluation of hydrologic data for computer analysis, the study area has been divided along township, range, and section lines to form 132 cells of 130 or 260 hectares (320 or 640 acres) each. All hydrologic data have been evaluated using these cell divisions. The volume of ground water in storage and the total storage capacity were not determined for the Stony Point area and the northern part of Meacham Hill, because these areas are included in the Santa Rosa Plain study area. For continuity, cells in the area northwest of the city of Petaluma have been included in both the Santa Rosa Plain model and the Petaluma Valley.

Basic data available for the Petaluma Valley were compiled and evaluated in several different ways. Water well logs were used to develop geologic cross sections showing the subsurface geology.

* A list of references is presented following Chapter 8.

**Conversion factors for changing from metric to customary units are listed on the inside back cover.

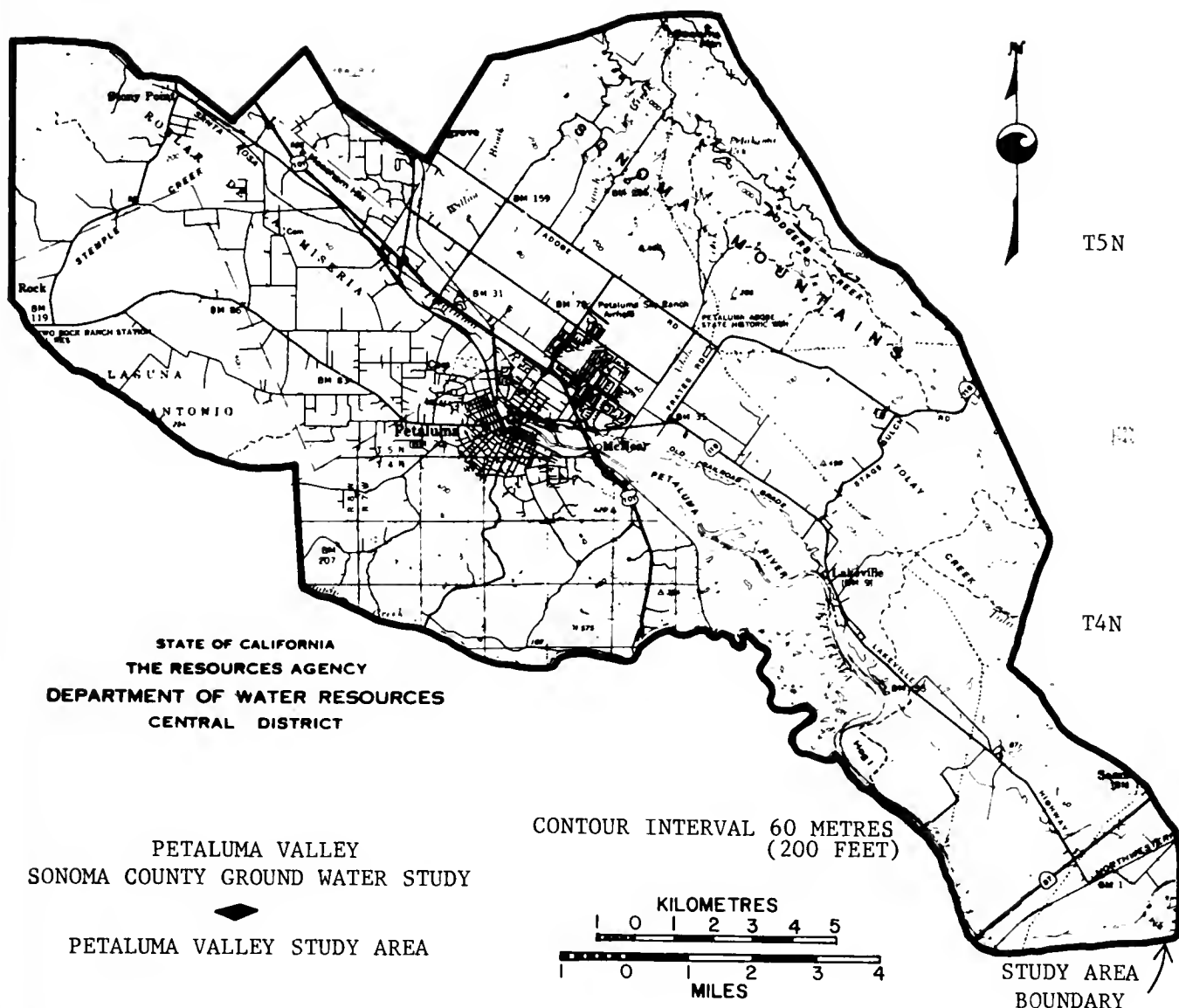
FIGURE 1



R8W

R7W

FIGURE 2



The well log information on types of materials encountered in each well was coded as input to the TRANSCAP computer program. The log information is compiled by cells to estimate the total ground water storage capacity for each cell. When combined with fall 1980 water level information, the total volume of ground water in storage and the total storage space available to receive recharge were determined.

It was assumed that all ground water in the study area is unconfined. The TRANSCAP program is discussed in more detail in Chapter 4.

All available water quality data were tabulated and plotted on topographic maps. This information was evaluated to determine regional water quality types as an indicator of aquifer continuity. Special water quality problems, such as high nitrate, sodium, and salinity, were evaluated to determine areal extent, source, and potential for migration of the affected water.

Soil maps developed by the U. S. Department of Agriculture Soil Conservation Service (Miller, 1972) were used to classify lands according to slope and soil infiltration rate. Those soils on

slopes of less than 15 percent and with an infiltration rate greater than 1.5 centimetres (0.6 inch) per hour have been tentatively classified as ground water recharge areas (after Muir and Johnson, 1979). Additional study may indicate that different infiltration rates may be more appropriate for this area.

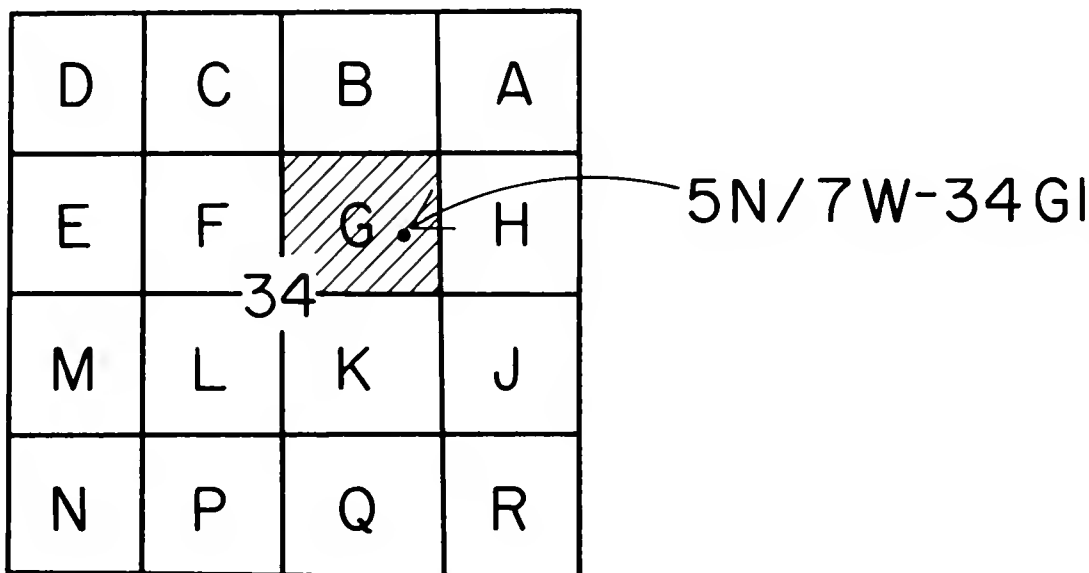
Data from the investigation were insufficient to provide accurate estimates of the annual quantity of ground water recharge in the Petaluma Valley. Some suggestions for a data collection program to determine this rate are included in this report (see Chapter 8).

The water well numbering system used in this bulletin is based on the rectangular system of subdivision of public land. When Sonoma County was first settled, most valley lands became parts of 25 land-grant ranchos. Lands outside of the land grants became public lands and were surveyed into townships of 36 square kilometres (36 square miles) that were

referenced to the Mount Diablo base and meridian. Each township was divided into 36 sections of roughly 2-1/2-square-kilometres (one-square-mile) each. Because land-grant areas do not have surveyed township, range, and section lines, these have been projected for the purpose of numbering water wells.

A State well number has two basic parts: its township location and its section location. For example, Well 5N/7W-34G1 is located in Township 5 North, Range 7 West, and Section 34; this places the well east of Petaluma. Each section is subdivided into 16 quarter-quarter sections of 16 hectares (40 acres) each; each 16-hectare tract is identified by a letter. Letters A through R are used, with letters I and O omitted to avoid confusion with similar appearing numbers. This particular well is in Tract "G", which also can be described as the southwest quarter of the northeast quarter of Section 34 (Figure 3). The final part of the well number is the sequential number of the well within that particular tract.

FIGURE 3



WELL NUMBERING SYSTEM

CHAPTER 2. CONCLUSIONS AND RECOMMENDATIONS

Major conclusions and recommendations of this study are summarized below.

Conclusions

- ° Ground water in Petaluma Valley is compartmentalized due to the discontinuous nature of most of the water-yielding deposits and to extensive faulting, which reduces the thickness of water-yielding deposits and may impede ground water flow. However, the western uplands underlain by the sandy Merced Formation have a high degree of vertical and horizontal aquifer continuity.
- ° The total storage capacity of the Petaluma Valley ground water basin is estimated to be 2 092 300 cubic dekametres (dam^3) (1,697,000 acre-feet (ac-ft)). The thickness of the water-yielding material ranges from 0 to 200 metres (m) (0 to 660 feet (ft)), with an average thickness of 87 m (185 ft). In the sandy western uplands, the water-yielding Merced Formation averages 150 m (450 ft) in thickness. The total volume of ground water in storage as of fall 1980 was 1 751 300 dam^3 (1,420,000 ac-ft). This figure includes water of all quality types, including brackish water caused by sea water intrusion.
- ° Nitrate contamination in the area northwest of Petaluma has made about 21 000 dam^3 (17,000 ac-ft) of ground water unsuitable for drinking. Sea water intrusion in the southern portion of the valley has made an additional 88 000 dam^3 (71,000 ac-ft) of ground water unsuitable. This reduces the total ground water in storage that is suitable for use to 1 642 300 dam^3 (1,332,000 ac-ft).
- ° Based on TRANSCAP, the volume of storage available to accept recharged surface water as of fall 1980 was 341 000 dam^3 (277,000 ac-ft). This represents 16 percent of the total storage capacity. Because of topographic constraints, ground water in the study area rarely fills more than 84 percent of storage capacity. Since the ground water reservoirs are therefore essentially "full", an artificial recharge program to increase the volume of ground water in storage is not needed at this time.
- ° Using available water level data and available data concerning the hydraulic properties of the sediments in the ground water reservoir, the average annual recharge is estimated to be 50 000 dam^3 (40,000 ac-ft) under present operational conditions. This recharge generally takes place in the Merced Formation and in some areas of alluvial fan deposits. Recharge also takes place in the Sonoma Volcanics; direction and rate of movement of this recharged water are unknown.
- ° Hydrographs of wells monitored during the 1976-1977 drought indicate that more surface water could be stored underground if more storage space were made available. This suggests that if ground water pumping were increased, more surface water runoff could be retained as ground water recharge. At present, much water runs off the land surface as rejected recharge.
- ° The area northwest of Petaluma contains a large proportion of the total ground water in storage in the Petaluma Valley. It also contains much of the total storage space available in the Petaluma Valley to accept recharge

- water. Proportionately more land surface (30 percent) in this northwest area has been classified as recharge areas than in the Petaluma Valley as a whole (20 percent).
- ° Ground water quality is generally poor in the Petaluma Valley. Much shallow ground water in the area northwest of Petaluma is contaminated by nitrates; ground water from near the base of the Merced Formation frequently has a high electrical conductivity. Poor quality water fills the few aquifers near San Pablo Bay; there is a potential for renewed sea water intrusion near Petaluma.
 - ° Nitrate contamination is a serious problem in the area northwest of Petaluma. Based on recent water quality analyses, generally the top 15 m (50 ft) extending down from the land surface are affected. A lack of vertical and horizontal barriers in the sediments of the upland area will allow the contaminated ground water to spread.
 - ° Both sea water intrusion and connate water affect the few water-yielding zones in the bay mud deposits in the southern portion of the valley. Sea water intrusion has affected aquifers in alluvial fan deposits near Petaluma. Existing water quality data, although limited, suggest little change in the extent of intrusion over the past 20 years.
 - ° When artificial recharge becomes necessary, alternative methods and sites should be studied so that recharge is optimized.
 - ° The area northwest of Petaluma contains potential recharge sites, but care should be taken to avoid moving nitrate-contaminated ground water into presently uncontaminated or unpolluted areas.
 - ° A program of ground water quality sampling should be implemented south of Petaluma to monitor possible inland movement of sea water. If sea water is found to be moving inland, mitigation measures should be explored, including (1) reduction in ground water pumpage near the intruded area; and (2) artificial recharge of ground water via injection wells near the intruded area, because geologic conditions make percolation ponds impractical.
 - ° Nitrates in the ground water northwest of Petaluma are currently being studied by DWR, Central District (Perkins, in progress). Sonoma County Ordinance 2607 requires that new wells in this area be built "... with an annular seal of at least 50 feet, but in no case less than into the first impervious structure." A deeper seal (Ritchie, 1981, Water Well Standards), from ground surface to 30 m (100 ft), would reduce the likelihood of well contamination by shallow, nitrate-contaminated wells.

Recommendations

- ° A program to determine streamflow infiltration rates and evapotranspiration should be implemented to more accurately determine the recharge rate of the Petaluma Valley.
- ° Ground water level monitoring of the 29-well network should be continued in order to improve estimates of change in storage and flow patterns.
- ° Ground water pumpage in the area northwest of Petaluma can be maintained at present levels, and possibly increased, if deep wells with 15- to 30-m (50- to 100-ft) sanitary seals are used. Ground water elevations in the study area should be measured biannually and examined periodically for large declines in the ground water table. Ground water pumpage from alluvial fan deposits near Petaluma can be maintained at present levels, but increases in pumpage to historical high volumes will renew sea water intrusion into this area.

CHAPTER 3. OVERVIEW OF GROUND WATER GEOLOGY, HYDROLOGY, AND SOILS

This chapter presents a brief overview of the ground water geology, hydrology, and soils of the Petaluma Valley. A detailed description of these subjects has been previously published in DWR Bulletin 118-4, Volume 1 (Ford, 1975).

Geology and Hydrology

Geologic formations in the Petaluma Valley can be divided into water-yielding formations, nonwater-yielding formations, and formations with highly variable water-yielding properties (Figure 4). Water-yielding formations are: alluvium, alluvial fan deposits, and the Merced Formation. Water-yielding formations that generally produce only low yields of ground water are bay mud deposits and the Petaluma Formation. Yields from the Petaluma Formation are higher when a well intercepts a lens of gravel. The Franciscan complex is nonwater-yielding (Plate 1). The Sonoma Volcanics and Tolay Volcanics have highly variable water-yielding properties; because of this variability, yields and the volume of ground water in storage in these units cannot be estimated as accurately as with other units.

Geologic characteristics of these units and their specific yields are summarized on Table 1. The areal distribution of these units is shown on Plate 1. The subsurface distribution of these units has been determined along the cross-section lines indicated on Plate 1 and Figure 5A as A-A', B-B', C-C', and D-D'. Profiles of the four cross sections are shown on Figures 5B-E. The following paragraphs briefly describe the geologic units, beginning with the oldest rocks.

In the following geologic descriptions, well yields have been described as limited or low, moderate, and high.

"Limited" or "low" yield means yields generally range from 5 to 380 litres per minute (L/min) (1 to 100 gallons per minute (gal/min)). With such yields, dry holes are common. "Moderate" yields generally range from 380 to 1 100 L/min (100 to 300 gal/min). "High" yields generally exceed 1 100 L/min (300 gal/min). The yield of a well is directly related to the hydraulic conductivity of the formation it penetrates. For more information on well yields, see Ford (1975).

Franciscan Complex

The Franciscan complex is the oldest geologic unit in the study area (Jurassic and Cretaceous age -- see Figure 6). It is exposed along the western and southwestern edges of the study area, and east of Lakeville Highway along Tolay Creek (see Plate 1). The complex includes highly variable amounts of shale, sandstone, chert, greenstone, and serpentinite. The Franciscan complex generally contains only limited quantities of water in fractures. Normally, consolidated rocks containing water only in fractures are not considered to have a specific yield. However, for this report, the Franciscan complex has been assigned a very low apparent specific yield of less than 3 percent. Because of the very low specific yield, areas composed of the Franciscan complex were not included in calculations of storage capacity in Chapter 4.

Tolay Volcanics

The Tolay Volcanics is of Miocene to early Pliocene age. It is present east of the Tolay fault at a depth of several hundred metres (Morse and Bailey, 1935). It is exposed in the vicinity of Petaluma

(Continued on page 18)

FIGURE 4

GROUND WATER TERMINOLOGY

The science of ground water hydrology deals with the distribution and behavior of ground water -- how much water is contained in any geologic material and how easily it can be extracted. The science of ground water geology deals with the effect of geology on the distribution and movement of ground water -- how different geologic materials and geologic structures determine the rate and paths of movement of ground water. By knowing the geology of an area, the subsurface hydraulic properties of that area can be estimated, because ground water hydrology and ground water geology are closely related.

Geologic formations can be divided into two groups: water-yielding and nonwater-yielding. Water-yielding formations, which usually consist of unconsolidated deposits of sand and gravel, readily absorb, transmit, and yield large quantities of ground water to wells. Nonwater-yielding formations, which usually consist of clay and consolidated rocks, yield only limited quantities of water to wells. Each geologic formation has specific hydraulic properties: porosity, permeability, specific yield, and transmissivity.

POROSITY AND PERMEABILITY

Porosity is the ratio of the volume of the voids between the particles in a sample to the total volume of the sample.

$$\text{Porosity} = \frac{\text{volume of voids}}{\text{total volume of sample}} (100) = \%$$

Porosity is not necessarily indicative of permeability, which indicates the ease with which ground water moves through a material. If the openings between the particles are small or are not connected, the permeability of the material is low. For example, clay contains a large number of small voids, so its porosity may be as high as 50 percent. Because of the physical and chemical nature of clay, it transmits very little water and it has a very low permeability, about 1.07×10^{-4} metres (3.5×10^{-4} feet) per day.* The porosity of sand and gravel is about 20 percent, much lower than the porosity of clay, but the voids in the sand and gravel are larger and are interconnected. Thus, most sands and gravels transmit water readily, having a permeability of about 1.07×10^2 metres (3.5×10^2 feet) per day.

A permeable geologic unit is called an aquifer. A relatively impermeable geologic unit is called an aquiclude or an aquitard because it retards the flow of water; both are called confining beds because they block the movement of ground water. Confining beds usually consist of clay or other fine-grained sediments. They contain ground water but have low permeability and cannot transmit extractable quantities. Granite is an example of an aquifuge because ground water cannot flow through it; granite is neither porous nor permeable. Ground water does flow through joints in the granite, but that geologic complication is a result of structural complexities not related to porosity or permeability. The porosity and permeability of formations composed of clay, sands, and gravels generally decrease through time as the formation becomes more consolidated.

SPECIFIC YIELD

Specific yield is the ratio of the volume of water that will drain due to gravity from a saturated sample of material to the total volume of the sample.

$$\text{Specific Yield} = \frac{\text{volume of water drained}}{\text{total volume of sample}} (100) = \%$$

The higher the specific yield of a geologic unit, the more water it will yield. Listed below are representative specific yield values for common geologic materials. Geologic materials having a more uniform grain size distribution will have a greater specific yield because of the greater total amount of space between particles. Consolidated rock and rocks such as basalt and granite are given specific yield values close to zero because water is contained only in fractures and not within the rock. The volume of water stored in fractured rock is highly variable, depending on the size and extent of the fractures, and cannot be easily quantified.

% Specific Yield	3	5	10	20	25
Geologic Material	Adobe Clay Shale	Cemented Gravel Cemented Sand Clay and Gravel Silt	Clay, Sand, & Gravel Fine Sand Quicksand Sand and Clay	Coarse Sand Loose Sand Medium Sand	Gravel Sand and Gravel

TRANSMISSIVITY

Transmissivity is the rate at which ground water will flow through a unit width of an aquifer, and is equal to the permeability of an aquifer multiplied by its thickness. The transmissivity of an aquifer or formation can generally be determined only from water level data collected during extended pumping of a water well. During a constant-rate pump test, abrupt changes in the slope of the curve from which transmissivity is determined indicate either the presence of a barrier, which impedes ground water movement, or the presence of a source of ground water recharge.

*"Metres per day" and "feet per day" are standard velocity units that indicate the amount of ground water that moves through a given cross-sectional area in one day:

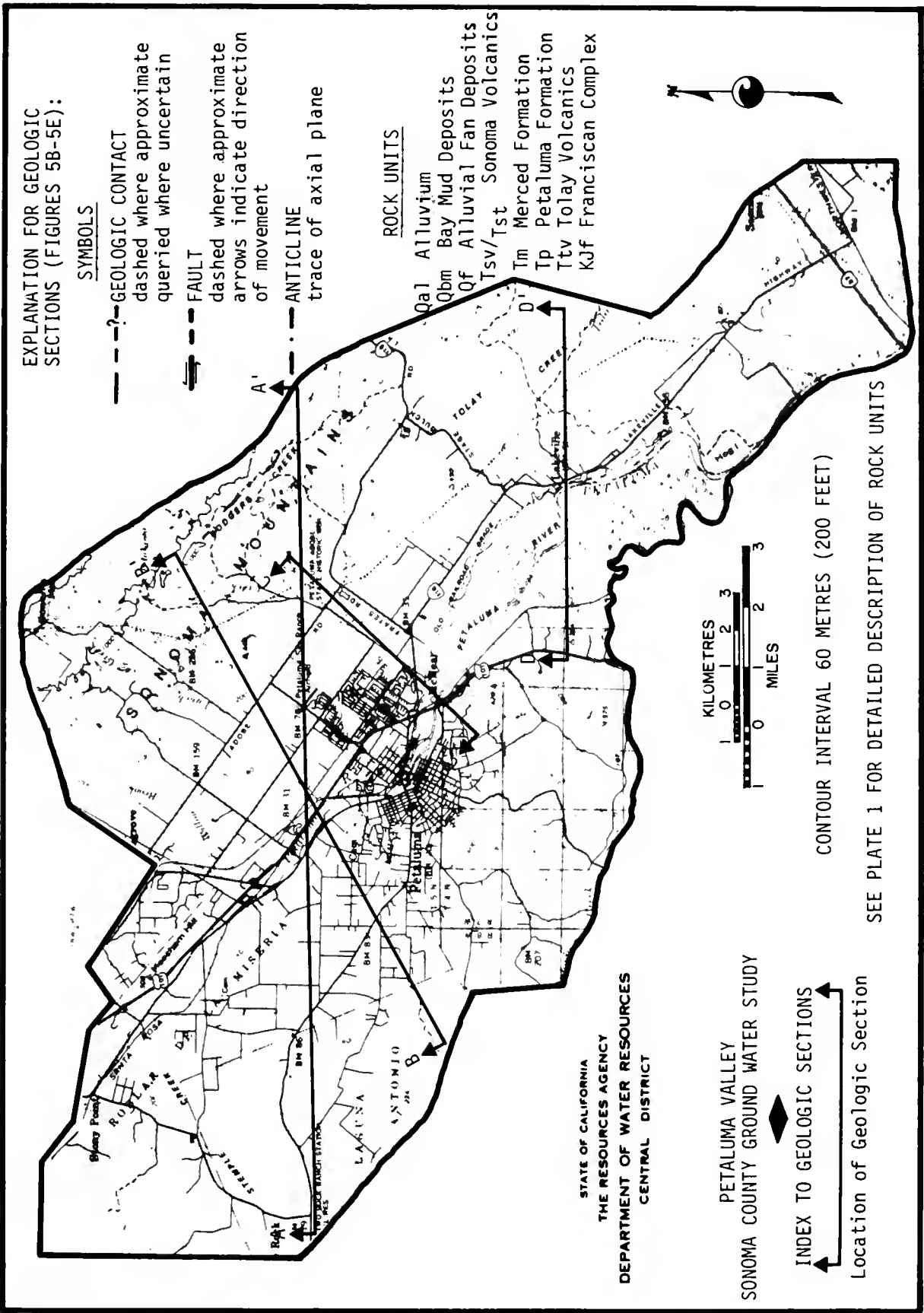
- 1 cubic metre of ground water moves through 1 square metre in 1 day. The units are: $1 \text{ m}^3 / \text{m}^2 / \text{day} = 1 \text{ m/day}$
- 1 cubic foot of ground water moves through 1 square foot in 1 day. The units are: $1 \text{ ft}^3 / \text{ft}^2 / \text{day} = 1 \text{ ft/day}$

Table 1
GEOLOGIC UNITS IN THE PETALUMA VALLEY^{1/}

Geologic Unit :	Lithology ^{2/}	Specific Yield :	Comments
Bay Mud Deposits Qbm	Mud, rich in organic matter, silty mud, silt, and fine sand.	Very Low (<3%)	Low yields. Generally contain brackish water, either connate or as the result of intrusion.
Alluvium Qal	Unconsolidated sand, silt, clay and gravel.	Variable (3-15%)	Moderate to high yields. Water quality is excellent. Minor amounts of methane gas. Lenses of very fine sand.
Alluvial Fan Deposits Qf	Unconsolidated fine sand, silt, and silty clay, coarse sand and gravel, with gravel more abundant near fan heads.	Moderate to high (8-17%)	
Sonoma Volcanics Tsv	Volcanic flows (labeled Tsv on Plate 1) and tuff, agglomerate, and volcanic sediments (Tst).	Highly variable (0-15%)	Variable yields, yields from Tst generally higher. Boron in some water may affect plants. Some waters thermal.
Merced Formation Tm	Coarse- to fine-grained sandstone with minor amounts of clay.	High (10-20%)	Generally high yields. Minor amounts of hydrogen sulfide (H ₂ S). Lenses of very fine sand. Zones of high concentration of methane gas.
Petaluma Formation Tp	Consolidated clay and shale with minor amounts of sandstone.	Low (3-7%)	Generally low yields. Yields may be higher for wells penetrating lenses of coarse material. Zones of hydrogen sulfide (H ₂ S).
Tolay Volcanics Ttv	Volcanic flows, tuffs, breccias, and agglomerates.	Highly variable (0-10%)	Variable yields. Fair to good water producer west of City of Petaluma.
Franciscan Complex KJf	Melange, including chert, sandstone, shale, greenstone, and serpentinite.	Very low (<3%)	Low yields. Poor quality water in thermal areas, serpentinite. Good water quality south of City of Petaluma.

^{1/} After Ford (1975, Table 1).

^{2/} Data from Blake, et al (1971); Fox, et al (1973); Blake, et al (1974).



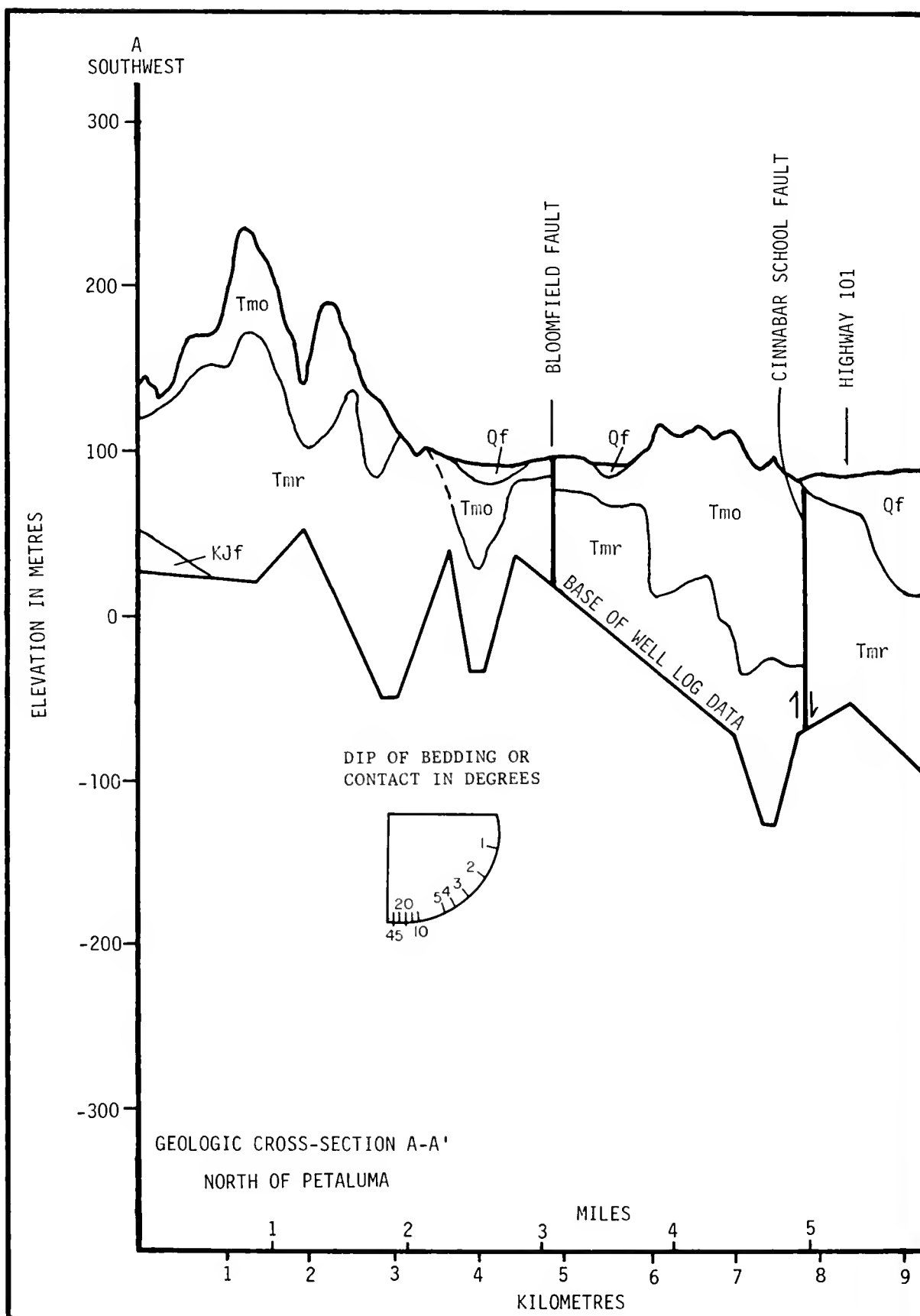
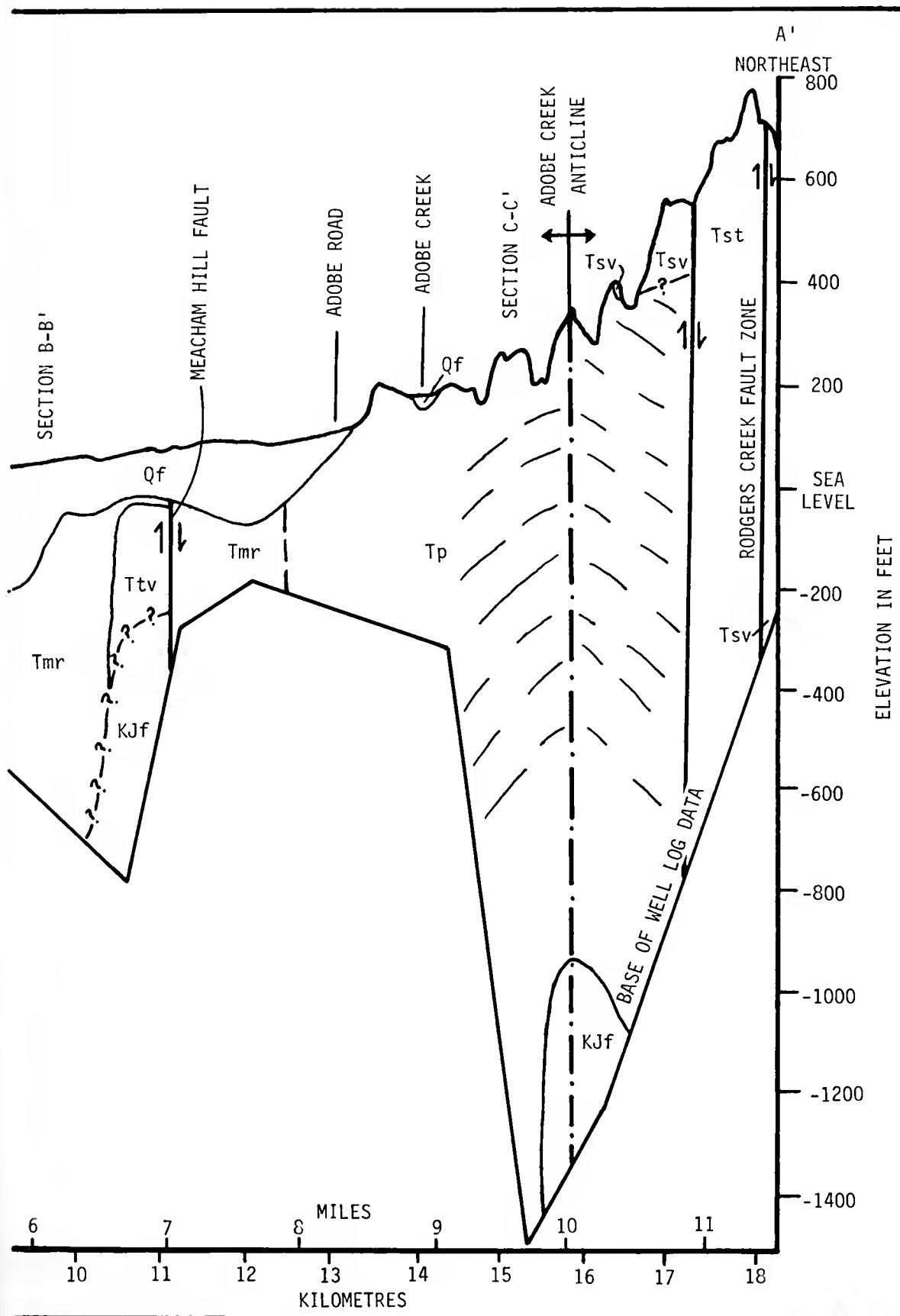


FIGURE 5B



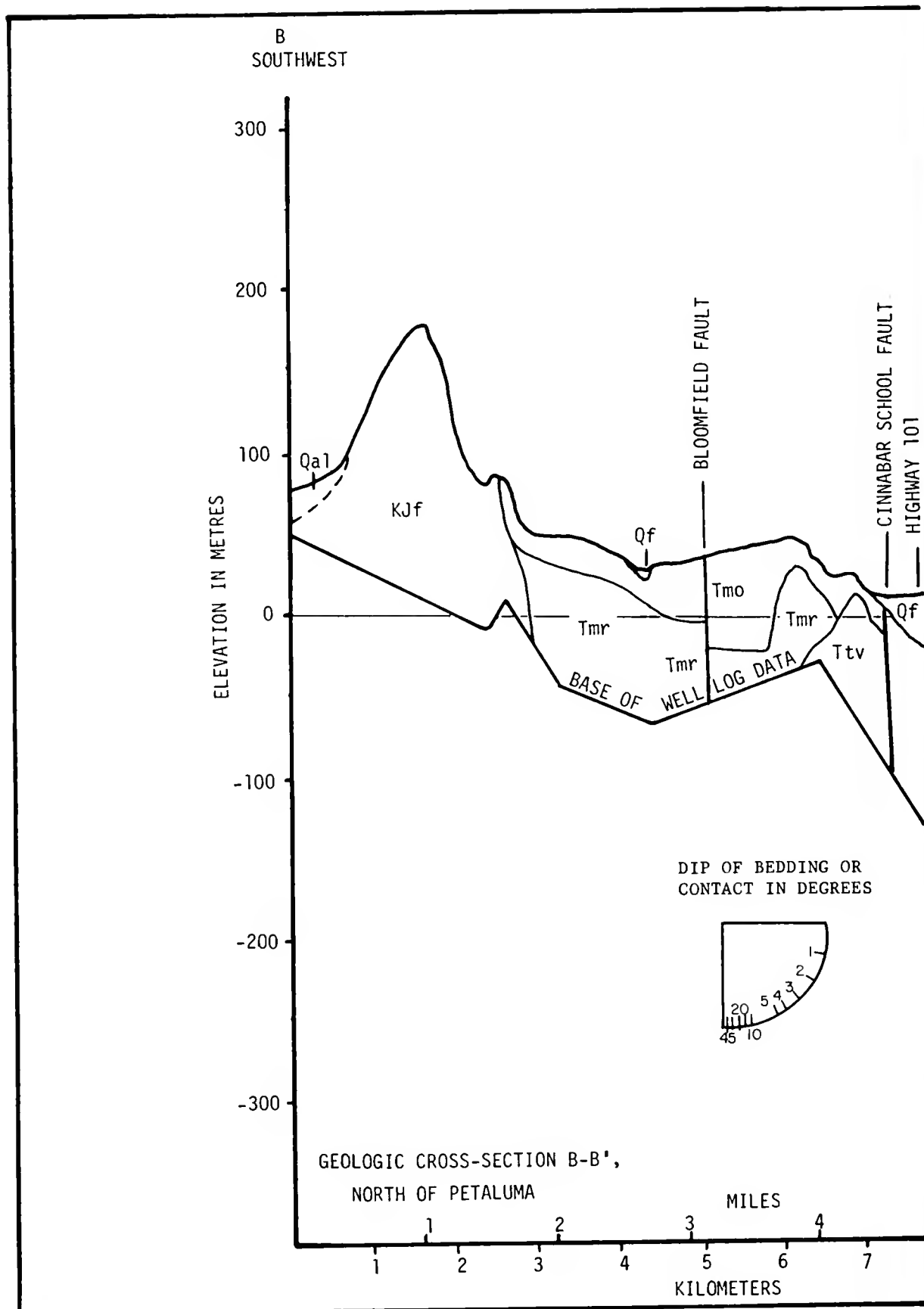


FIGURE 8C

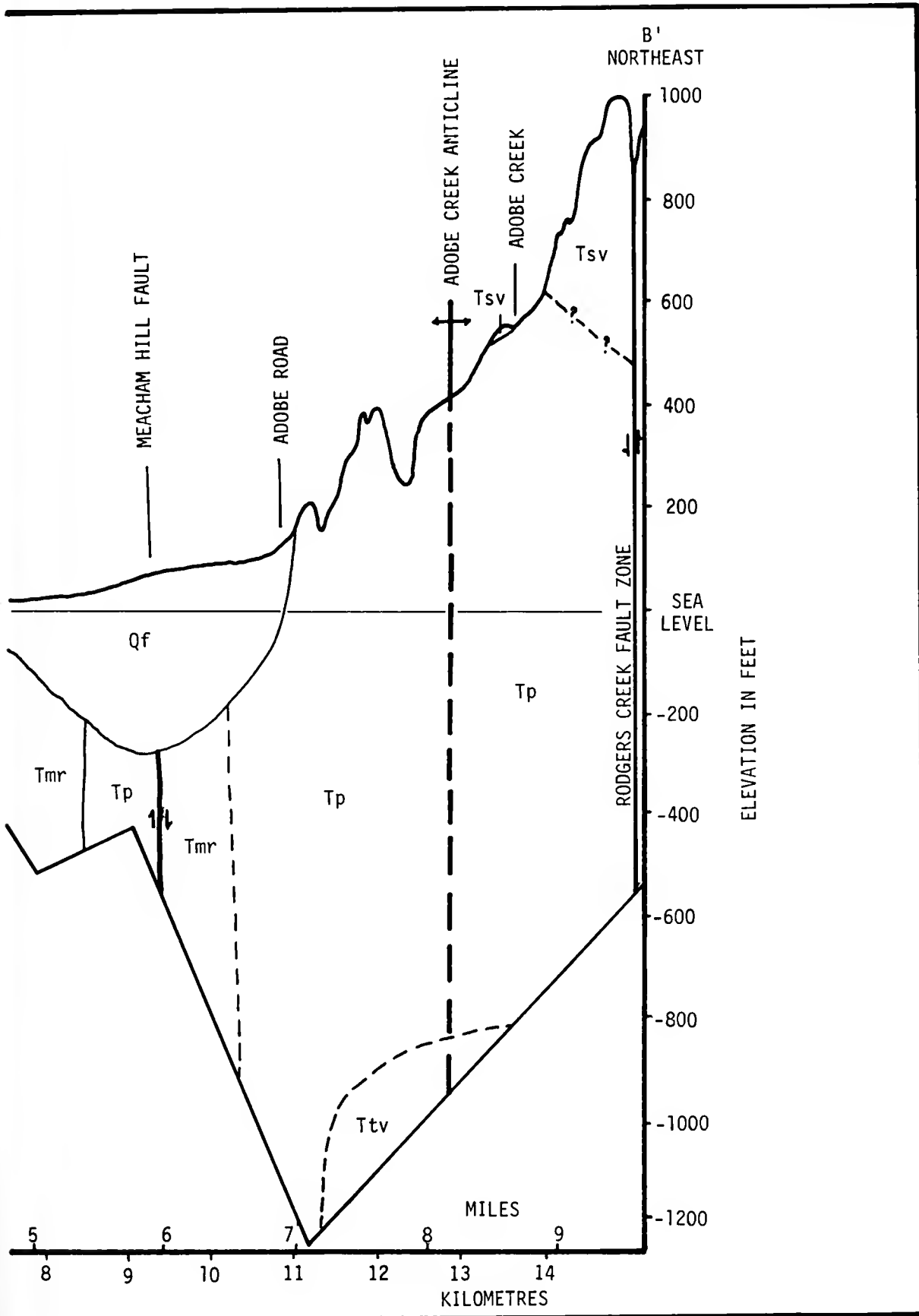
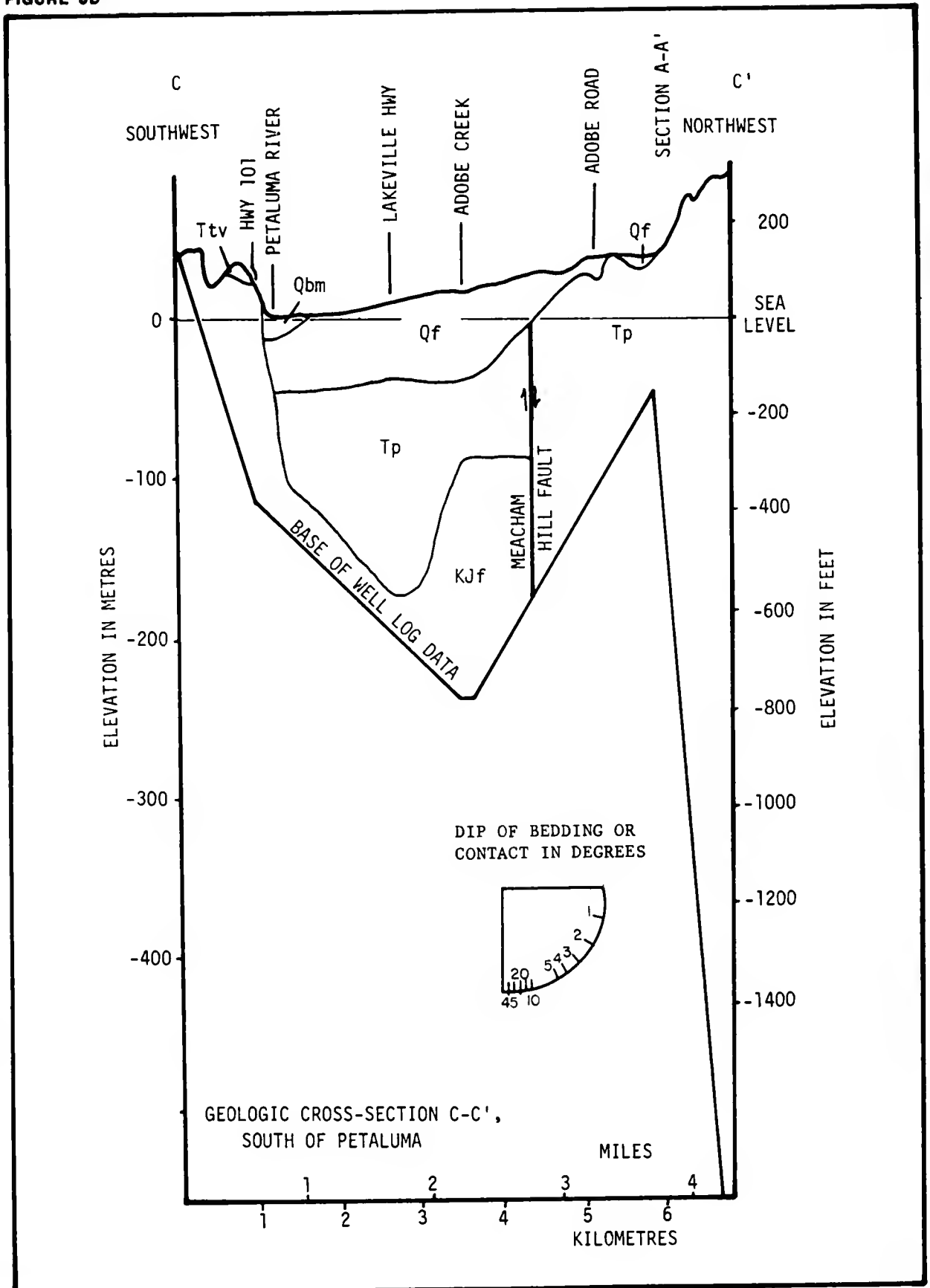


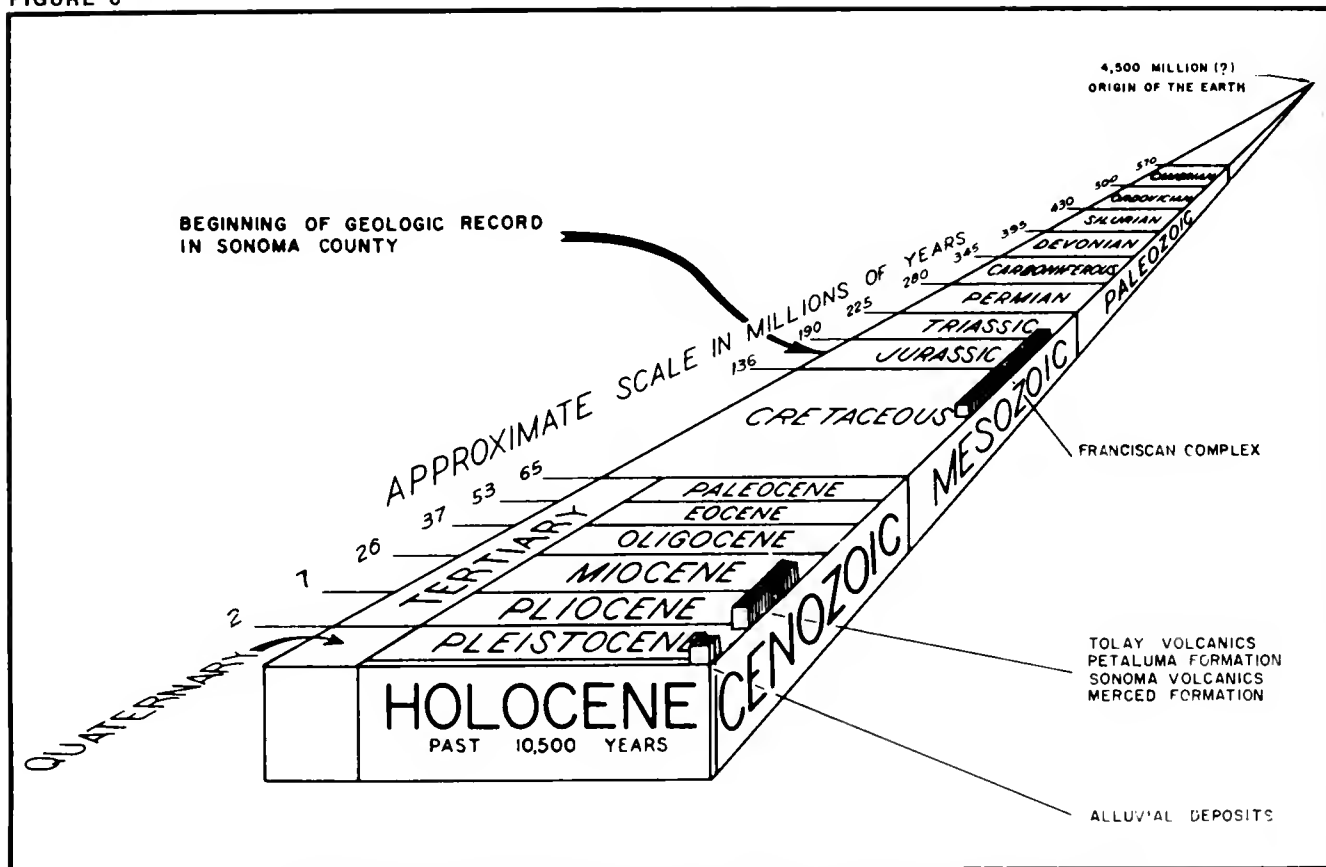
FIGURE 8D



NORTHEAST



FIGURE 6



LOOKING BACK IN GEOLOGIC TIME—PETALUMA VALLEY

and is present at shallow depths of 45 m (150 ft) immediately to the west of Petaluma. Although originally mapped as Sonoma Volcanics, these rocks have been identified as Tolay in this report based on new age data. These dates are from:

- ° Burdell Mountain, Marin County (11.8 ± 0.8 million years (MY) (Mankinen, 1972)).
- ° Basalt Rock Company quarry immediately east of Petaluma (12.0 ± 0.5 MY (Garniss H. Curtis to Basalt Rock Company, written communication, 1969))
- ° Volcanic rocks along Spring Hill Road (11.76 MY) and from Meacham Hill (13.62 MY (Kenneth F. Fox, Jr., written communication, 1981)).

The unit, defined by Morse and Bailey (1935) from oil well core samples, includes a great thickness of lava flows, breccias, tuffs, and agglomerates. In some areas west of Petaluma, stream channel deposits are interbedded with the volcanic flow rocks.

The Tolay Volcanics has a highly variable specific yield. It is considered to be a fair-to-good water producer in some areas

west of Petaluma (Ford, in progress). In other parts of the Petaluma Valley, the lava flows are essentially nonwater-yielding except where the rocks have been highly fractured by faults. Normally, consolidated rocks containing water only in fractures are not considered to have a specific yield. However, for this report, the Tolay Volcanics has been collectively assigned a variable apparent specific yield of from 0 to 10 percent. Because of the variable water-yielding characteristics, areas composed of Tolay Volcanics were not included in calculations of storage capacity in Chapter 4.

Petaluma Formation

The Petaluma Formation, mid-to-late Pliocene in age, is exposed in the mountains east of the Petaluma River. The Petaluma Formation consists of folded continental and shallow marine to brackish-water deposits of clay, shale, and sandstone, with lesser amounts of conglomerate and nodular limestone. Occasional thick beds of diatomite are present. Abundant clay characterizes this unit; Weaver (1949) measured a 323-m (1,059-ft) thick stratigraphic section near Lakeville in the Petaluma Valley containing 70 percent clay, shale, and clayey or shaley beds. Hydrogen sulfide has been found in wells penetrating the Petaluma Formation in the Santa Rosa Plain. The Petaluma Formation can yield moderate amounts of water when a well penetrates an appreciable thickness of sand and gravel. However, because of the large amounts of clay that characterize the unit, it has been assigned a low overall specific yield of from 3 to 7 percent.

Merced Formation

The Merced Formation, generally Miocene to Pliocene in age, is one of the principal water-yielding formations in Sonoma County. It is exposed in the uplands on the northern and western sides of the Petaluma Valley.

In these uplands, the Merced consists of an upper oxidized continental unit of brown sandstone, clay, and gravel, and a lower reduced shallow-marine unit of blue sandstone and blue sandstone with shells. The two units are separated by an erosional surface, and sometimes by lava flows of the Sonoma Volcanics. Both units are excellent aquifers, and when the volcanic rock is not present, there appears to be good hydraulic continuity between the upper and lower units. Where the volcanic rock is present, water in the lower unit is confined; some wells in the vicinity of Paulsen Lane that pump water from the lower unit, below the volcanics, have heads of approximately 15 m (50 ft). Some ground water in the upper unit is also confined (based on information from water well logs). Since no confining beds can be located from existing subsurface data, confinement may be due to local cementation of overlying sandstone.

The reduced Merced unit underlies the Petaluma Valley at a depth of 76 m (250 ft). Cardwell (1958) noted that the permeability of the Merced is lower in the southeastern part of the Petaluma Valley than in the northwestern part.

Marine fossils are abundant within the reduced Merced unit and are generally recorded as oysters or clamshells on water well drillers' logs. Also common within the formation are zones of poorly consolidated, very fine sand, frequently reported by drillers as "quicksand". High concentrations of methane gas have been noted in the Merced in the central portion of the Santa Rosa Plain. Hydrogen sulfide has been reported in a Petaluma municipal well that bottomed in the Merced. Since the Merced is predominantly sandstone, it has a high specific yield of from 10 to 20 percent.

Sonoma Volcanics

The Sonoma Volcanics, of Pliocene age, is exposed along the crest of the Sonoma Mountains on the eastern edge of the study area. In this area, the Sonoma

Volcanics consists of a thick sequence of lava flows (labeled Tsv on Plate 1) with minor intrusive igneous rocks consisting of rhyolite, perlite, and rhyolite breccia. In some areas, such as near Rodgers Creek, lava flows are inter-layered with tuff, welded tuff, and volcanic sedimentary deposits, such as tuffaceous sand and volcanic gravel (labeled Tst on Plate 1). Large landslides have been mapped by Fox, et al. (1973) in areas underlain by Sonoma Volcanics.

The Sonoma Volcanics has a highly variable specific yield. It is considered to be a good water producer where unwelded tuff, scoria, and volcanic sediments are present. In the Petaluma Valley, the lava flows and intrusive rocks are essentially nonwater-yielding except where the rocks have been highly fractured. Normally, consolidated rocks containing water only in fractures are not considered to have a specific yield. However, for this report, the Sonoma Volcanics has been collectively assigned a variable apparent specific yield of from 0 to 15 percent. Because of the variable water-yielding characteristics, areas composed of Sonoma Volcanics were not included in calculations of storage capacity in Chapter 4.

Alluvial Fan Deposits and Alluvium

Alluvial fan deposits of Pleistocene and Holocene age form a nearly continuous blanket over the northern Petaluma Valley and along the eastern edge of the southern Petaluma Valley. They consist of poorly sorted coarse sand and gravel and moderately sorted fine sand, silt, and silty clay; gravel content increases near the heads of fans. Fan deposits in the southern Petaluma Valley are generally finer grained.

Lenses of very fine sand within the alluvial fan deposits frequently cause sanding problems in water wells. This

sand is similar to the very fine-grained sand present in the Merced Formation; the Merced may be, in part, a source of this alluvial fan sand.

Minor amounts of methane gas have been noted in fan deposits in the southern Santa Rosa Plain. The gas may have risen from an underlying formation, such as the Merced, and been trapped within the fan deposits by overlying impermeable clay.

Because of the unconsolidated, coarse-grained nature of much of the alluvial fan deposits, they have been given a moderate to high specific yield of 8 to 17 percent.

Alluvium of Pleistocene to Holocene age forms a thin surficial deposit along Tolay Creek, Stemple Creek, and other creeks in the Petaluma Valley. It is composed of interbedded sand, silt, clay, and gravel. The specific yield of these deposits is variable, depending on the amount of clay present and the thickness of the deposit. Most are less than 30 m (100 ft) thick with specific yields ranging from 3 to 15 percent.

Bay Mud Deposits

Bay mud deposits of Holocene age cover the southern Petaluma Valley. They are bay and marsh deposits, generally composed of mud, silty mud, silt, and small amounts of sand, and are rich in organic material. They have been covered in many areas by artificial fill. The bay mud was deposited during a higher stand of sea level, and much sea water was trapped in the sediments as they were deposited; bay mud is still being deposited on the floor of San Pablo Bay. Since little fresh water has moved through the bay muds since they were deposited, water pumped from them is generally brackish to highly saline. The bay muds have a low permeability and a very low specific yield of less than 3 percent.

Folds and Faults

Ground water reservoirs can be modified by folds and faults. Layered geologic formations can be bowed upward and downward by regional geologic forces to form anticlines and synclines, respectively. Because the hydraulic conductivity in these formations prior to folding is usually highest in the horizontal direction and lowest in the vertical, ground water usually flows away from the axis, or core, of an anticline and toward the axis of a syncline. In both cases, this is the direction of highest permeability.

Many folds are present in the Petaluma Formation in the Petaluma Valley; one of the largest is the Adobe Creek Anticline. It may be the feature that separates the Petaluma Valley and Santa Rosa Plain ground water basins. No large folds have been mapped in the Merced Formation, but the Merced as a whole dips slightly to the east. Younger geologic formations have not been folded.

Faults are fractures in the rock along which the rocks on either side have been moved. The fracture might or might not intersect the earth's surface. Faults are widespread in the Petaluma Valley and surrounding mountains. Faults sometimes create zones of crushed and broken rock along the fault plane. This crushed material, known as gouge, consists of clay-sized particles and can impede the movement of ground water across the fault, thus acting as a ground water barrier. In contrast, faults in brittle rocks can shatter the rocks, forming zones of high permeability. Faults can also affect ground water movement by thinning water-yielding sands and gravels on the upthrown side of the fault; higher topographic relief increases the rate of erosion. Water-yielding materials may be thicker on the downthrown side if sediments are being deposited during a period of continued downward movement of one side of the fault.

Major faults in the Petaluma Valley are the Rodgers Creek, Tolay, Bloomfield, and two faults that have not previously been recognized; they are here named the Meacham Hill fault and the Cinnabar School fault (Plate 1).

The Rodgers Creek fault, known to be active, is actually a zone of faulting just west of the crest of the Sonoma Mountains. The 1969 earthquake that extensively damaged Santa Rosa was centered on this fault. Because of the fault's location, it probably has very little effect on aquifers beneath the valley floor. Because the fault may impede the flow of recharging ground water moving downslope toward the valley, and because many of the rocks in the mountainous areas are essentially nonwater-yielding, areas east of the Rodgers Creek fault trace were not included in calculations of storage capacity in Chapter 4.

The trace of the Tolay fault parallels Tolay Creek and the Lakeville Highway. The fault has influenced valley aquifers by bringing the nonwater-yielding Franciscan complex to the surface along the western side of its fault trace. There are no indications of a direct connection between the Tolay fault and a northwestern extension of the Tolay fault published by Fox (1973); water levels do not change across the projected trace and there are no recognizable displacements of geologic units, based on subsurface data from water well drillers' logs. The southern trace of the Tolay fault has been designated as potentially active under the Alquist-Priolo Special Studies Zones Act of 1972. "Potentially active" means that evidence has been found which indicates that movement along the fault occurred within the last 2 million years, or during Quaternary time.

The trace of the Bloomfield fault extends north and west of the City of Petaluma. First mapped by Travis (1952), it was later extended from data compiled by

Koenig (1963). Ford (in press) has extended the fault farther to the south-east and connected it with an unnamed fault mapped by Blake (1974), based on subsurface data from water well logs. The sense of vertical displacement on the fault changes from northwest to southeast. Presently available data are not sufficient to determine the effect of the fault on ground water.

The trace of the Meacham Hill fault crosses the southwestern flank of Meacham Hill, where it is delineated by a line of springs. On Meacham Hill, the fault emplaces Sonoma Volcanics against the Merced Formation (G. D. Woodard, personal communication, 1980). In 1943, Johnson mapped an unnamed fault at this location; he estimated the maximum throw to be 90 m (300 ft). Farther south along the trace, the Meacham Hill fault has brought Tolay and Franciscan rocks near the surface along the western side of its fault trace. This displacement is similar in sense and magnitude to that along the southern trace of the Tolay fault. Geologic sections constructed from well drillers' logs indicate that the southern trace of the Tolay fault and the Meacham Hill fault are connected.

Ground water level contours steepen in the vicinity of the fault trace (see Figure 10), indicating that transmissivity may be reduced across the Meacham Hill fault trace.

The Cinnabar School fault offsets the Merced Formation at the base of the hills northwest of Petaluma. This fault extends northwestward to connect with the Tolay fault of Fox (1973) and extends southeastward along the base of the hills as far as Lynch Creek, based on subsurface data from water well logs (Ford, in press). Geophysical anomalies identified by Harding-Lawson Associates (1976) as caused by the Tolay fault appear instead to be related to the Cinnabar School fault. The fault brings the upper oxidized Merced Formation into contact with the lower reduced Merced. The upper

oxidized Merced Formation does not appear east of the fault trace. The effect of this fault on ground water in the area cannot be determined from presently available data.

Soils

Soil is a product of many factors:

- ° The geologic formation that underlies it and from which it formed.
- ° The slope of the land.
- ° Age of the soil.
- ° Climate, especially the amount of rainfall.
- ° Organisms, especially native vegetation.

Of these factors, geology is the most important. For example, the sandy soils in the vicinity of Petaluma formed from the Merced Formation, which is composed predominantly of sandstone. The heavy soils in the southern Petaluma Valley were formed from bay mud deposits, which are largely clay. Slope generally affects the thickness of the soil profile, with thicker, older soils forming on flatter slopes. Age of the soil and the amount of rainfall control the degree to which the soil profile develops into distinct layers or "horizons". Young soils, especially in arid climates, have relatively little profile development. Organisms modify soil characteristics such as the amount of nitrogen and organic matter in the soil.

In turn, soil characteristics control the types of crops that can be grown in an area, the amount of surface water that infiltrates to the ground water body, and the effectiveness of septic-tank leach-field sewage disposal systems. Agricultural crops usually grow best on deep, permeable soils. Some nearly impermeable

adobe soils are suitable only for pasture. Permeable soils are necessary for recharge of surface water to the ground water body unless an artificial recharge program is initiated. Soils that have neither a very high infiltration rate (infiltration rate faster than 2 minutes per centimetre or 5 minutes per inch) nor a low infiltration rate (infiltration rate slower than 25 minutes per centimetre or 60 minutes per inch) are necessary for leach-field siting.

In general in the Petaluma Valley, permeable soils have formed on some alluvial deposits (labeled Qf and Qal on Plate 1), on some sedimentary units in the Sonoma Volcanics (Tst), on the Merced Formation (Tm), and on some portions of the

Petaluma Formation (Tp). Poorly permeable soils have generally formed on bay mud deposits (Qbm), on some units in the Sonoma Volcanics (Tsv), and on the Franciscan complex (KJf).

In this report, only soils with an infiltration rate greater than 1.5 centimetres (0.6 inch) per hour and a land slope less than 15 percent are considered to be permeable enough to allow recharge to ground water. These criteria were developed by the U. S. Geological Survey during recharge studies in the Santa Cruz area (Muir and Johnson, 1979). Approximately 20 percent of the study area has been tentatively classified as recharge areas. Locations of the recharge areas are discussed in Chapter 5.

CHAPTER 4. GROUND WATER SUPPLY IN THE PETALUMA VALLEY

Ground water supplies can be estimated once the geologic and hydrologic characteristics of a basin are understood. In Petaluma Valley, the volume of potable water is reduced by nitrate contamination in the area northwest of Petaluma and by sea water intrusion near San Pablo Bay and along lower Petaluma River. The potential for increased sea water intrusion governs the volume of fresh ground water that should be extracted in Petaluma Valley.

The study area contains 1 751 300 dam³ (1,420,000 ac-ft) of ground water in water-yielding materials that average 87 m (285 ft) in thickness. Long-term annual extractions from the study area should not exceed the average annual recharge to the study area if permanent depletion of the ground water in storage is to be avoided. Using the results of the computer program TRANSCAP and ground water well data from 1950 through 1980, the average annual recharge to the study area was estimated to be 50 000 dam³ (40,000 ac-ft). The estimated volume of ground water pumpage in the Petaluma Valley in 1980 was 9 600 dam³ (7,800 ac-ft) (derived from Finlayson, 1980, Table 13). If natural recharge rates could be determined more accurately, a sustained yield figure could be calculated; sustained yield would more accurately reflect the ground water potential of the basin than does the estimated average annual recharge given in this report.

Method of Investigation Using TRANSCAP

In the Petaluma Valley, the TRANSCAP (transmissivity and storage capacity) computer program was used to determine:

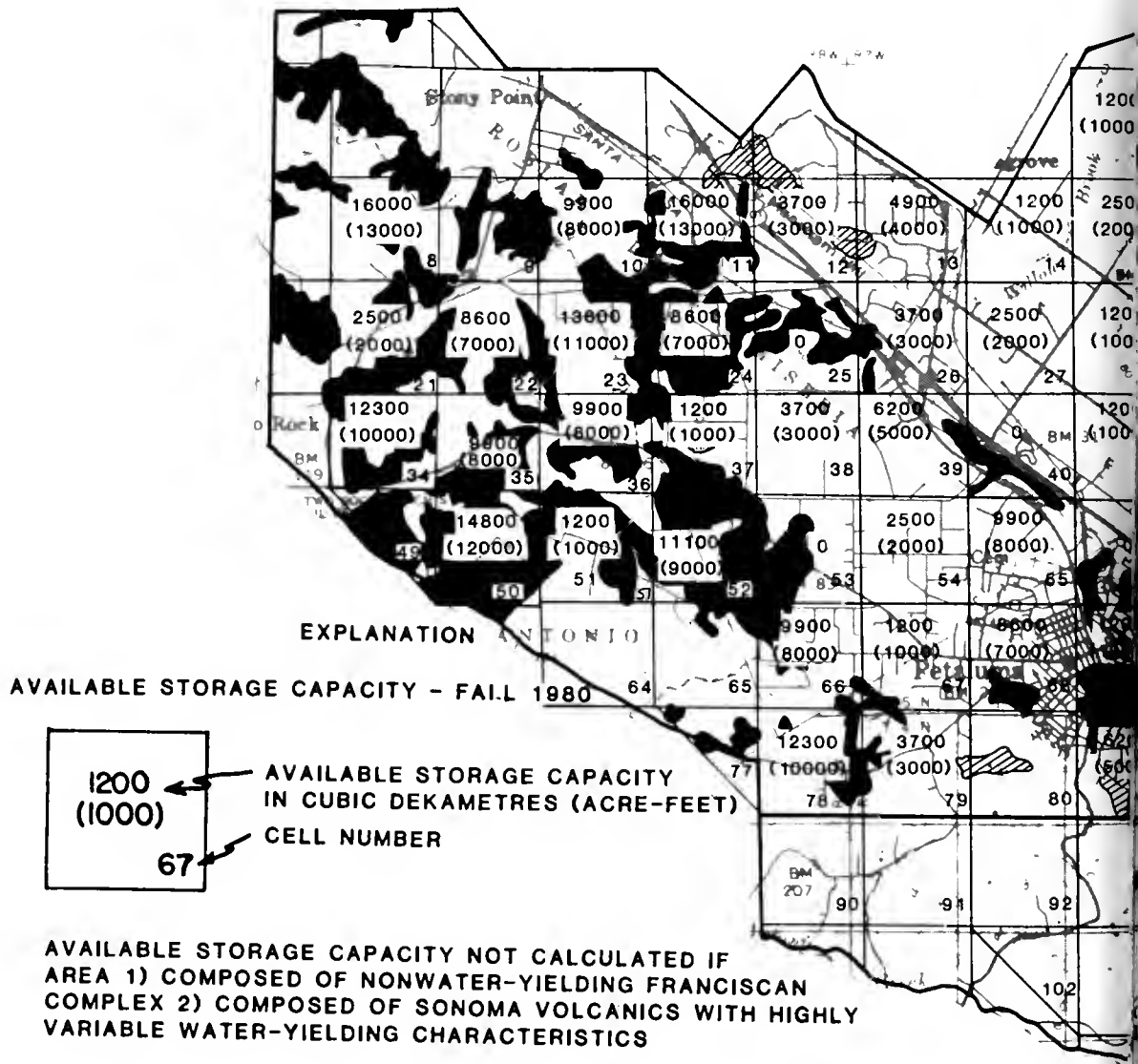
- ° Total storage capacity.
- ° Volume of ground water in storage.
- ° Volume of storage available to store recharge.
- ° Estimated annual natural recharge.

A detailed description of the TRANSCAP computer program is given in Miyazaki (1980).

The initial step in using TRANSCAP to study an area is to divide the area into "cells". In the Petaluma Valley, each cell is equivalent to a 260-hectare (640-acre) section, or to that portion of a section underlain by water-yielding materials. The study area and cell boundaries are shown on Figure 7.

Where the surficial geology is composed mainly of the Franciscan complex, cells were not evaluated because this complex is nonwater-yielding. Where the surficial geology is composed mainly of Sonoma or Tolay Volcanics, cells were not evaluated because volcanic rocks are highly variable in their hydrologic properties. Cells east of the trace of the Rodgers Creek fault were not evaluated because the fault may impede the flow of ground water toward the valley.

Water well drillers' reports are collected for each cell to be evaluated. A sample well driller's report is shown in Figure 8. The right-hand column of the report lists the geologic materials encountered during drilling of the well. The materials in each well are then coded into the computer according to their specific yield. This specific yield information is the basic data used by the TRANSCAP program.






STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
CENTRAL DISTRICT

PETALUMA VALLEY
SONOMA COUNTY GROUND WATER STUDY

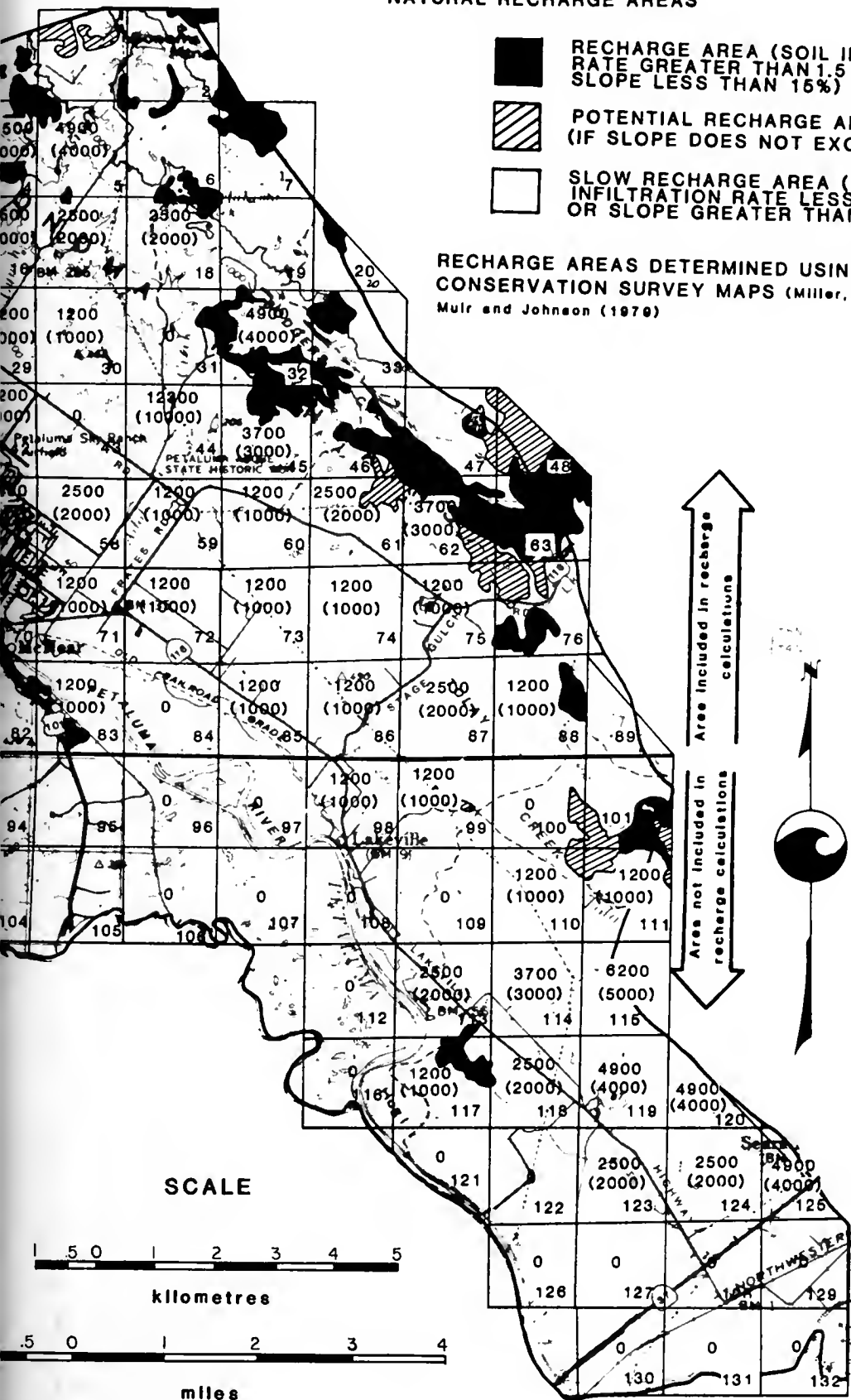
◆

AVAILABLE STORAGE CAPACITY
PER CELL AND AREAS OF NATURAL RECHARGE

NATURAL RECHARGE AREAS

-  RECHARGE AREA (SOIL INFILTRATION RATE GREATER THAN 1.5 cm/hr SLOPE LESS THAN 15%)
-  POTENTIAL RECHARGE AREA (IF SLOPE DOES NOT EXCEED 15%)
-  SLOW RECHARGE AREA (SOIL INFILTRATION RATE LESS THAN 1.5 cm/hr OR SLOPE GREATER THAN 15%)

RECHARGE AREAS DETERMINED USING U.S. SOIL CONSERVATION SURVEY MAPS (Miller, 1972) AFTER Muir and Johnson (1979)



The TRANSCAP program adjusts all wells within a cell to the average elevation of the land surface in that cell. The program then averages all specific yield data from all wells in a cell for specified depth intervals, generally 3 m (10 ft). The averaged specific yield data are converted to transmissivities using equations of a curve developed by the DWR investigation of the Livermore and Sunol Valleys (Ford and Hills, 1974). For specific yield values from 0 to 9, the curve is described by the equation:

$$\Delta T = \Delta D \cdot 10 \left[\frac{3.5319 - 7.16288}{|SY| - 0.84} \right]$$

and for specific yield values greater than 9, the curve is described by the equation:

$$\Delta T = \Delta D \cdot (100 |SY| - 500)$$

where ΔT = incremental transmissivity,
 ΔD = incremental depth, and
 $|SY|$ = absolute value for average specific yield for a given interval

When no drillers' logs were available for a cell, transmissivity and storage capacity values from another cell with similar geology were used.

A sample TRANSCAP printout in customary units is shown in Figure 9. The variables listed in the upper left-hand corner of the table describe the values used to set up TRANSCAP for this cell. Increment of Depth = 10 indicates that specific yields were averaged over 10-ft (3-m) intervals. Node Elevation Control is the average elevation of the land surface within the cell. Node Surface Area is the surface area, in acres, of the cell. Note that the center point in a cell is called the "node".

The figure describes hydrologic properties by intervals: either as "Depth" below land surface, or "Elevation" relative to sea level. For example, for the interval from 10 to 20 ft (3 to 6 m) above sea level or 80 to 90 ft (24 to 27 m) below land surface, the "average

specific yield" is 10.30 percent, the "unit width transmissivity" is 5,300 gallons/day (20 000 litres/day), and the "storage capacity" is 673 ac-ft (830 dam³). These computer-generated numbers are rounded to one or two significant figures before use, to avoid giving an erroneous impression of precision.

To determine the storage capacity of any cell, the bottom of the water-yielding zone must first be determined. The graph in Figure 9 entitled "unit width summation of transmissivity plot" shows a profile of the transmissivity in the sample cell. Points on the graph represent unit width transmissivity values that have been summed starting at the lowest elevation evaluated for the cell. Summed unit width transmissivity values are listed in the right-hand column labeled "TR VALUE" opposite the corresponding elevation. The numbers across the top of the graph are summed unit width transmissivities in thousands of gallons per day.

The point at the lowest elevation on the graph represents 0. As elevation increases, the points on the graph move from left to right, and the heading is read from left to right, lowest line first (0 to 500).

When the summed transmissivities exceed 500 thousand gallons per day, the graph doubles back, and the headings are read from right to left (500 to 1,000). When the summed transmissivities exceed 1,000 thousand gallons per day, the graph again doubles back and the headings are read from left to right (1,000 to 1,500).

The more horizontal the line on the graph, the more permeable the water-yielding zone. The more vertical the line, the more that zone functions as a confining bed. The bottom of the water-yielding zone is determined from the TRANSCAP graph and is verified by comparison with geologic maps and cross sections. The top of the water-yielding zone is generally assumed to be the land surface. The net storage capacity of the water-yielding zone is calculated

ORIGINAL

File with DWR

Notice of Intent No. _____

Local Permit No. or Date _____

STATE OF CALIFORNIA

THE RESOURCES AGENCY

DEPARTMENT OF WATER RESOURCES

WATER WELL DRILLERS REPORT

Do not fill in

No. SAMPLE

State Well No. _____

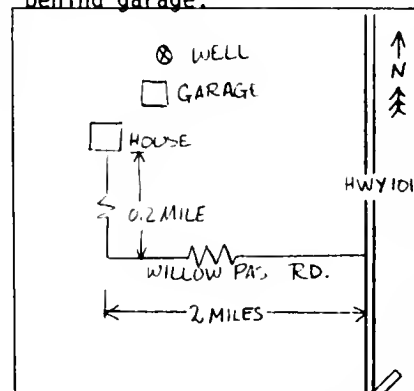
Other Well No. _____

(1) OWNER: Name Alice Mar
 Address 212 South Willow Pass Road
Woodlake, California Zip 93563

(2) LOCATION OF WELL (See instructions):
 County Sonoma Owner's Well Number 74-2

Well address if different from above:
 Township 7N Range 6W Section 19

Distance from cities, roads, railroads, fences, etc. 4 miles west of
Woodlake, 2 miles east of Highway 101, 0.2 mi.
north of Willow Pass Road, NE of house
behind garage.



(3) TYPE OF WORK:

New Well ☒ Deepening ☐Reconstruction ☐Reconditioning ☐Horizontal Well ☐Destruction ☐ (Describe

destruction materials and

procedures in Item 12)

(4) PROPOSED USE:

Domestic ☒Irrigation ☐Industrial ☐Test Well ☐Stock ☐Municipal ☐Other ☐

(5) EQUIPMENT:

Rotary ☒ Reverse ☐Cable ☐ Air ☐Other ☐ Bucket ☐

(6) GRAVEL PACK:

Yes ☒ No ☐ Size 1/8-1/4Diameter of bore 12"Packed from to

(7) CASING INSTALLED:

Steel ☒ Plastic ☐ Concrete ☐

(8) PERFORATIONS:

Type of perforation or size of screen

From ft.	To ft.	Dia. in.	Gap or Wall	From ft.	To ft.	Slot size
0	152	8"	1/4"	40	51	100
				129	143	

(9) WELL SEAL:

Was surface sanitary seal provided? Yes ☒ No ☐ If yes, to depth 50 ft.Were strata sealed against pollution? Yes ☐ No ☒ Interval ft.Method of sealing Cement Grout

(10) WATER LEVELS:

Depth of first water, if known 23 ft.Standing level after well completion 28 ft.

(11) WELL TESTS:

Was well test made? Yes ☒ No ☐ If yes, by whom? A-OK DrillingType of test Pump ☐ Bailor ☐ Air lift ☐Depth to water at start of test 23 ft.Discharge 100 gal/min after 24 hoursAt end of test 37 ft.Water temperature 67°FChemical analysis made? Yes ☒ No ☐ If yes, by whom? Dow LabWas electric log made? Yes ☒ No ☐ If yes, attach copy to this report(12) WELL LOG: Total depth ft. Depth of completed well ft.

from ft. to ft. Formation (Describe by color, character, size or material)

0 - 4 top soil

4 - 23 brown sandy loam

23 - 40 brown clay and gravel

40 - 41 coarse sand and pebble gravel

51 - 68 brown sandy with minor clay

68 - 92 blue sand

92 - 97 coarse sand with shell fragments

97 - 103 sand and pebble gravel with minor clay

103 - 125 red volcanic rock

125 - 129 black crystal vitric tuff

129 - 143 andesite

143 - 147 dark gray volcanic ash

147 - 152 scoria and volcanic ash

152 - 165 fractured andesite

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DWR 168 (REV. 7-76)

SAMPLE WATER WELL DRILLERS REPORT

by subtracting the "storage capacity to bottom" figure at the bottom of the water-yielding zone from the corresponding figure at the top of the water-yielding zone.

The program TRANSCAP calculates storage capacities to the bottom of the deepest well in each cell. No storage capacity information is available for that portion of an aquifer below the bottom of the deepest well. For cells where the aquifer extends below the well data, the storage capacity from TRANSCAP is a minimum value; the true storage capacity would be higher.

In the Petaluma Valley, the thickness of the water-yielding materials ranges from 0 to 200 m (0 to 660 ft), with an average thickness of 87 m (285 ft). The thickest sections are northwest of the City of Petaluma.

To determine the volume of water in storage, the average ground water level for the cell is determined from a ground water level map. The volume of water in storage is determined by subtracting the "storage capacity to bottom" figure at the bottom of the water-yielding zone from the corresponding figure at the ground water table elevation. This method assumes that all ground water in the cell is unconfined. If, however, ground water is confined, the volume of stored ground water estimated by this method will be too large. The more confined the ground water, the larger the error will be.

Water level information for fall 1980 (Figure 10) was combined with the product of TRANSCAP to determine the storage capacity, the total volume of water in storage, the available ground water storage capacity, and the amount of fresh water displaced by sea water in the Petaluma Valley. Available storage capacity indicates the capability of the cell to store additional ground water from natural or artificial recharge.

Available storage capacity (estimated for cells where no drillers' logs were

available) is given in Figure 7. The volume of ground water in storage per cell is presented in Figure 11.

Total Water in Storage and Available Storage Capacity

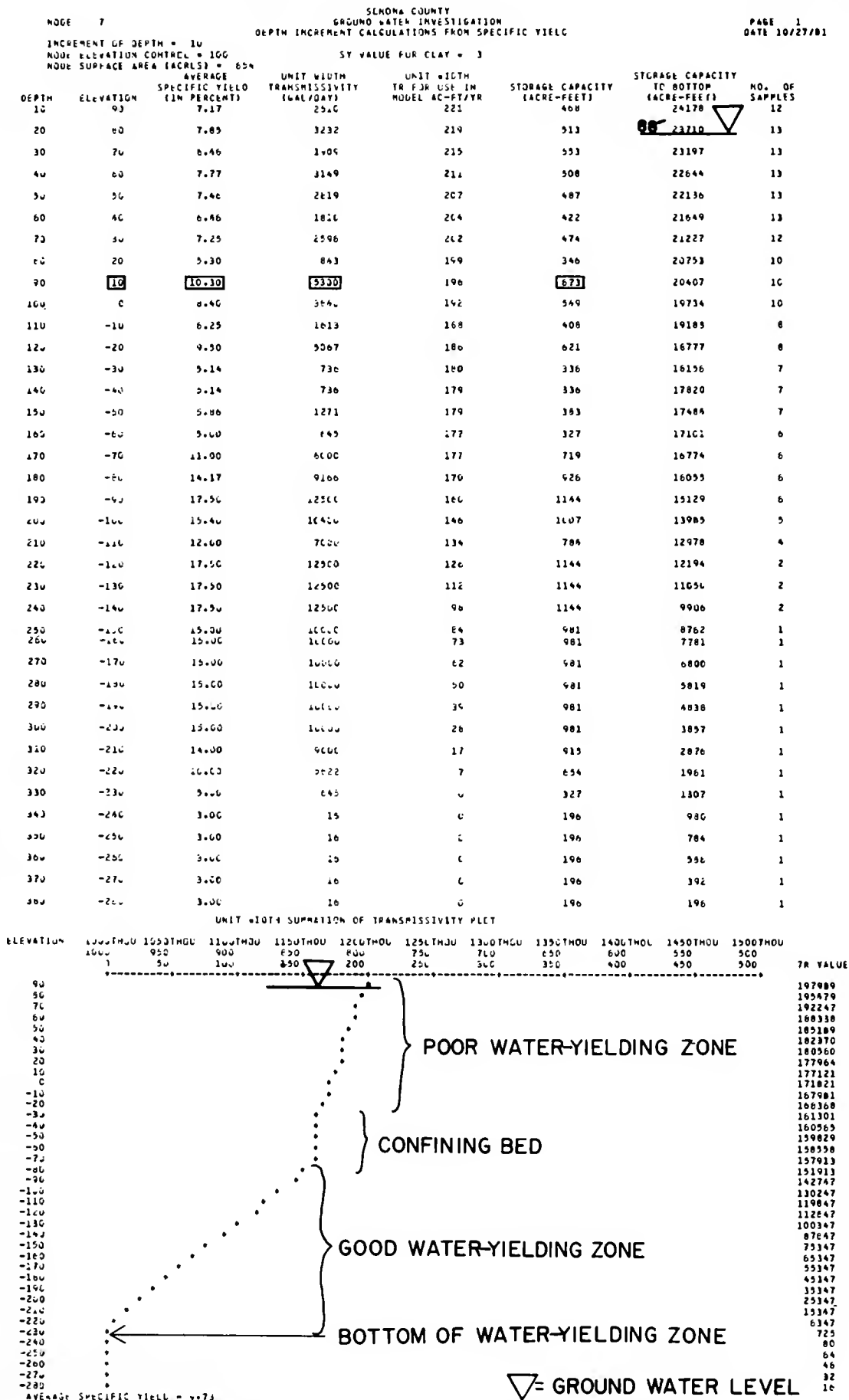
The total volume of water in storage and the available ground water storage capacity are given in Table 2. There were not enough ground water level data available before fall 1980 to construct ground water level maps, but hydrographs of wells that have been monitored in the past were examined for trends.

Ground water levels near the City of Petaluma dropped from the mid-1950s until the early 1960s. Ground water levels began to recover after introduction of imported water in 1962. In some cases, ground water levels returned to historic normal levels. Ground water levels have remained relatively steady since that time except during the drought of 1976-1977.

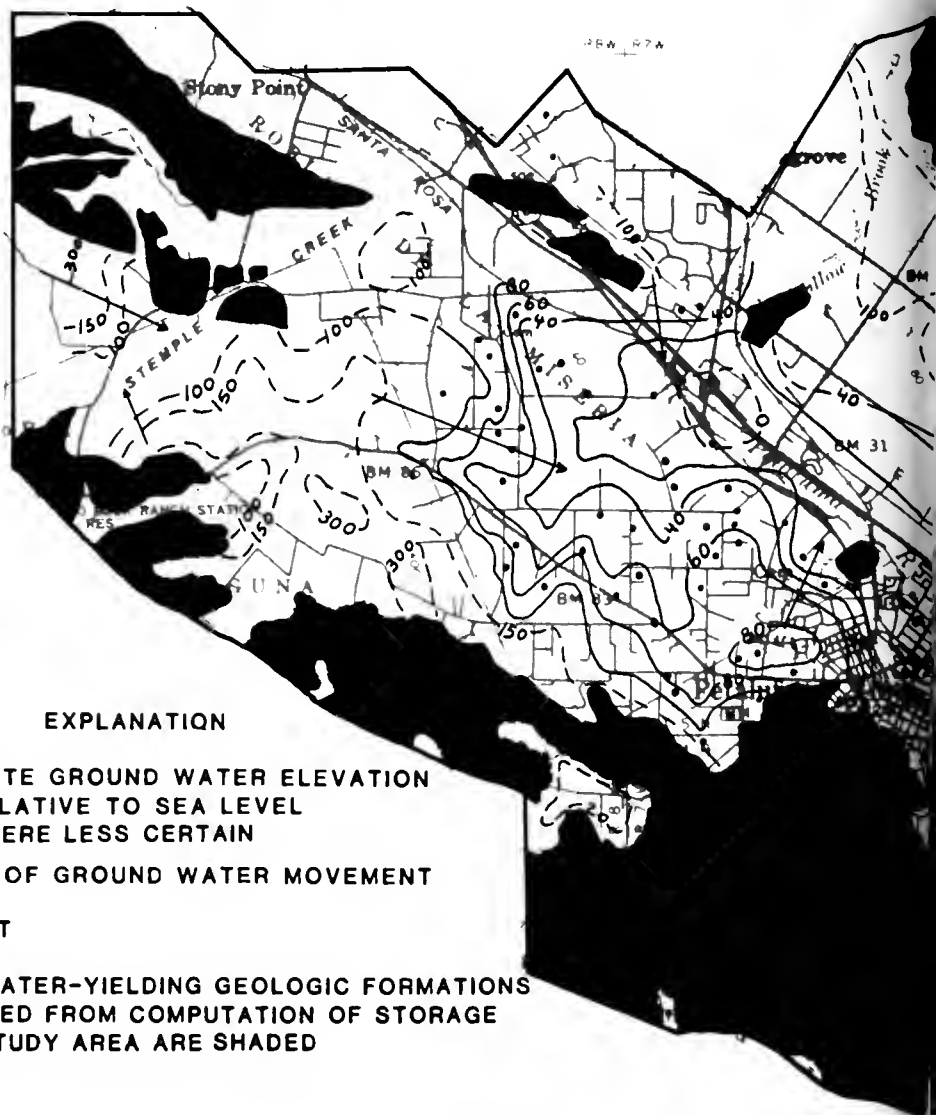
Ground water levels in monitored wells in the Petaluma Valley normally drop 3 m (10 ft) between the spring water level (highest of the year) and the fall water level (lowest of the year). During the 1976-1977 drought, ground water levels dropped an average of 3 m (10 ft) below the normal yearly low by the fall of 1977, but in most areas, levels had returned to normal by spring 1978. In general, therefore, the hydrographs indicate that the volume of ground water stored in the Petaluma Valley has not changed much over time.

Volume of Ground Water Affected by Nitrate Contamination

During the winter of 1978-79, a case of methemoglobinemia in an infant whose family lived in the upland area northwest of Petaluma sparked concern about nitrate concentrations in the ground water in that area. Testing of domestic wells during summer 1979 indicated nitrate



SAMPLE TRANSCAP PRINTOUT



EXPLANATION

- 150— — APPROXIMATE GROUND WATER ELEVATION
IN FEET RELATIVE TO SEA LEVEL
DASHED WHERE LESS CERTAIN
- DIRECTION OF GROUND WATER MOVEMENT
- DATA POINT

ESSENTIALLY NONWATER-YIELDING GEOLOGIC FORMATIONS
THAT WERE EXCLUDED FROM COMPUTATION OF STORAGE
CAPACITY IN THE STUDY AREA ARE SHADED

GROUND WATER ELEVATIONS CALCULATED FOR FALL 1980.

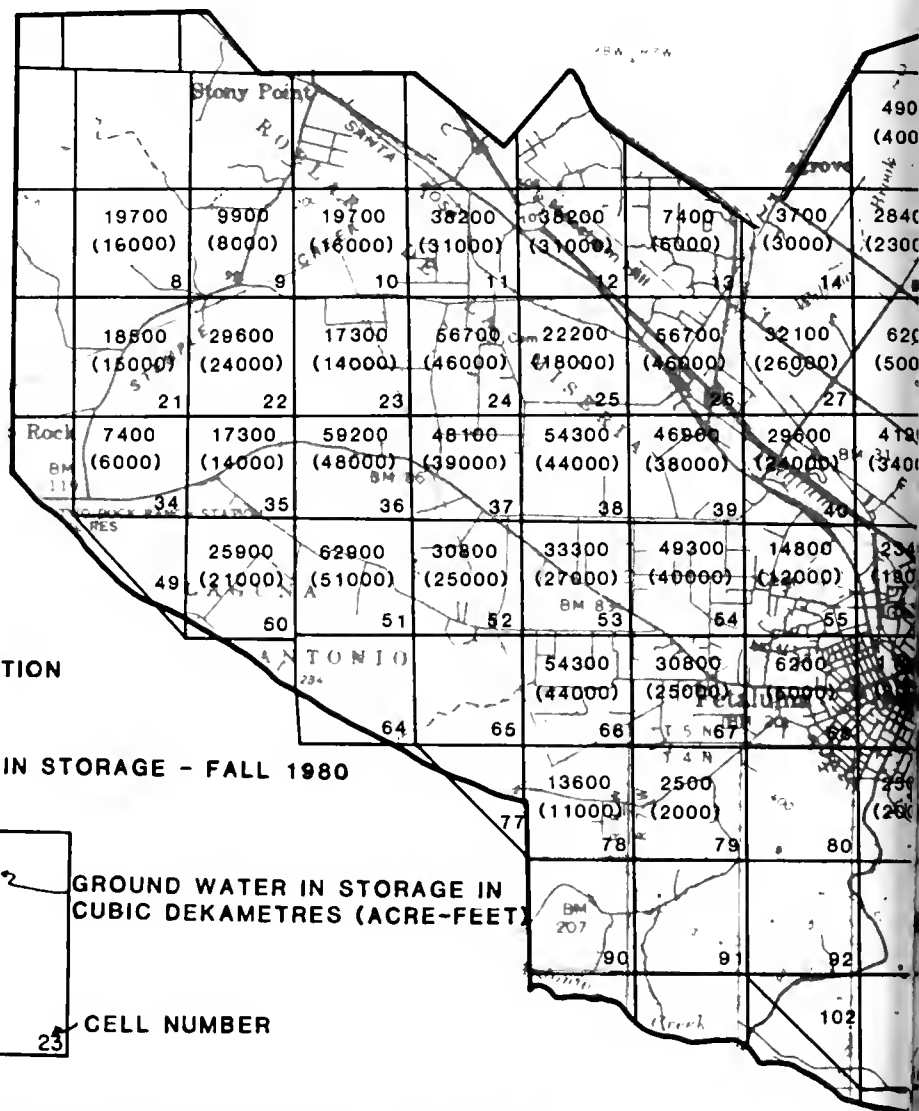
STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
CENTRAL DISTRICT

PETALUMA VALLEY SONOMA COUNTY GROUND WATER STUDY



GROUND WATER ELEVATIONS





GROUND WATER IN STORAGE NOT CALCULATED IF AREA
 1) COMPOSED OF NONWATER-YIELDING FRANCISCAN COMPLEX
 2) COMPOSED OF SONOMA VOLCANICS WITH HIGHLY VARIABLE WATER-YIELDING CHARACTERISTICS AREAS

STATE OF CALIFORNIA
 THE RESOURCES AGENCY
 DEPARTMENT OF WATER RESOURCES
 CENTRAL DISTRICT

PETALUMA VALLEY
 SONOMA COUNTY GROUND WATER STUDY



GROUND WATER IN STORAGE PER CELL

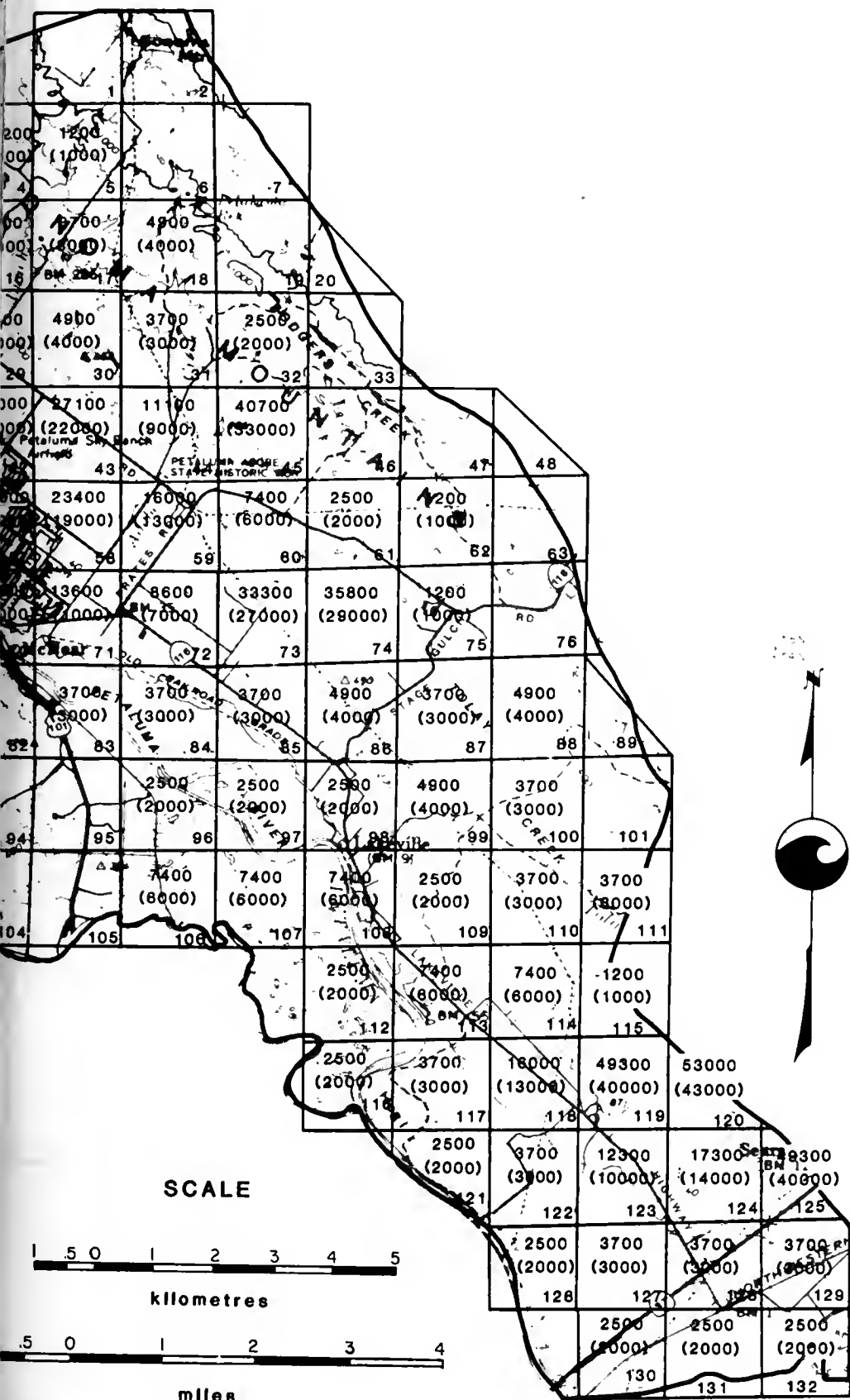


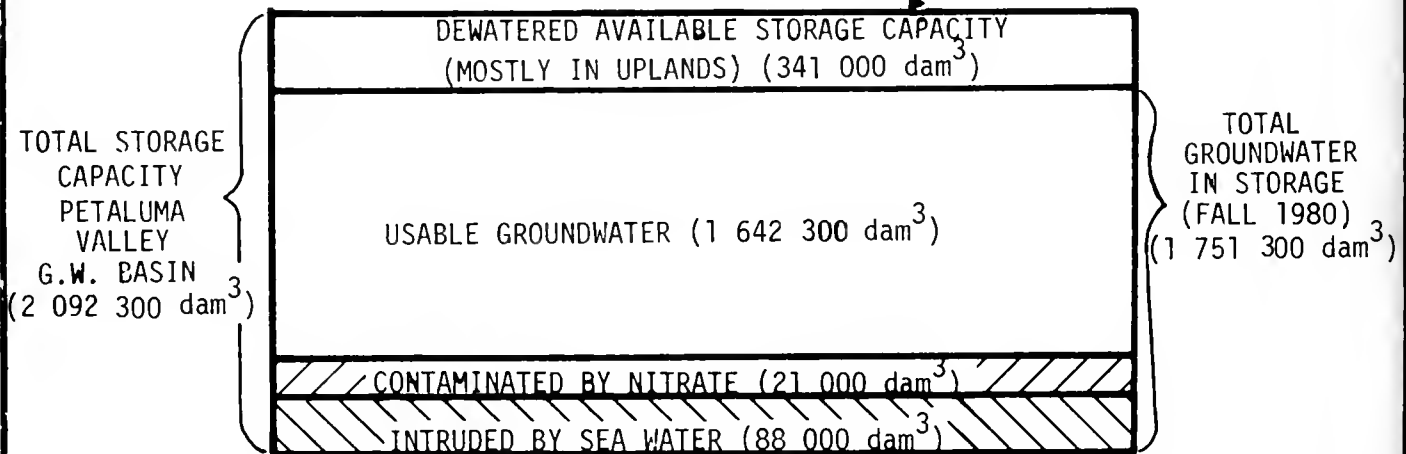
Table 2

GROUND WATER SUPPLY IN THE PETALUMA VALLEY

Total Storage Capacity	2 092 300 dam ³	(1,697,000 ac-ft)*
Available Storage Capacity	341 000 dam ³	(277,000 ac-ft)
Total Water in Storage (Based on fall 1980 ground water levels)	1 751 300 dam ³	(1,420,000 ac-ft)
Volume of Ground Water Seriously Affected		
by Nitrate Contamination (Area Northwest of Petaluma)	21 000 dam ³	(17,000 ac-ft)
Sea Water Intrusion	88 000 dam ³	(71,000 ac-ft)
Volume of Usable Water in Storage	1 642 300 dam ³	(1,332,000 ac-ft)
Estimated Annual Natural Recharge	50 000 dam ³	(40,000 ac-ft)
Percentage of Total Storage Capacity Dewatered		16%

*Because both metric and customary figures have been rounded, multiplying metric figures by 0.81070 will not give the customary figures.

ESTIMATED ANNUAL RECHARGE
(50 000 dam³)



concentrations in excess of recommended public health limits in 33 percent of the 200 wells tested.

There is evidence of serious nitrate contamination in wells located in 16 cells northwest of Petaluma (Figure 12). Sampling indicates that all contamination probably occurs within 15 m (50 ft) of the land surface. Assuming that the 16 cells (numbers 11, 23, 24, 37, 38, 52, 53, 54, 55, 56, 65, 66, 67, 68, 79, and the southwestern half of 40) are contaminated to 15 m (50 ft) below land surface, the total amount of water in storage that is unusable is 21 000 dam³ (17,000 ac-ft) (Table 3). This is a rural residential area, and houses are served water by individual wells averaging 55 m (180 ft) deep. Therefore, this volume of contaminated water represents 8 percent of the total water in storage in these cells that is currently being tapped by wells.

Because the Merced Formation, which underlies this area, has few barriers to vertical movement of ground water, contamination is likely to spread. If the sources of the nitrate contamination are not eliminated and the existing contamination is not removed, it is probable that the contaminated zone will eventually extend to 30 m (100 ft) below land surface in the presently contaminated cells. If so, the volume of contaminated water would be 60 000 dam³ (49,000 ac-ft), which represents 22 percent of the total water in storage in these cells that is being tapped by wells.

Because there are also few horizontal barriers to ground water movement on the Merced Formation, contamination could also spread to neighboring cells. The nearby cells most likely to be affected are cells 9, 10, 21, 22, 25, 34, 35, 36, 39, 50, 51, and the southwestern half of cells 12 and 26 (Figure 12). If the presently affected cells and these nearby cells were all contaminated to a

depth of 15 m (50 ft) below land surface, 32 000 dam³ (26,000 ac-ft) of ground water would be affected. This represents 7 percent of the total ground water supply currently used in these cells. Further contamination to 30 m (100 ft) would affect 21 percent of the currently used supply or 99 000 dam³ (81,000 ac-ft). The sampling program currently under way by DWR (Perkins, in progress) may indicate that some of these nearby cells are already affected.

Volume of Ground Water Affected by Sea Water Intrusion

Sea water intrusion generally affects the southern Petaluma Valley and areas adjacent to the tidal portion of the Petaluma River. The bay mud deposits in the southern part of the valley (Plate 1) generally contain brackish water that was trapped between the clay particles when the material was deposited. Farther north, along the Petaluma River, some of the alluvial fan deposits near the river produce brackish water as a result of inland movement of sea water in response to ground water pumping.

The bay mud and alluvial fan deposits are generally only affected to shallow depths of 30 m (100 ft). At present, the total volume of water lost in this interval because of intrusion is 88 000 dam³ (71,000 ac-ft). No attempt was made to calculate the volume of unpotable connate water in the Petaluma Formation.

In general, available data do not indicate any appreciable change over the last 20 years in the volume of ground water affected by sea water intrusion. Lack of change is probably a result of reduced ground water pumpage by Petaluma after imported Russian River water became available in 1962. As long as ground water pumpage near the tidal portion of the Petaluma River does not substantially increase, the volume of affected ground water should not increase.

FIGURE 12

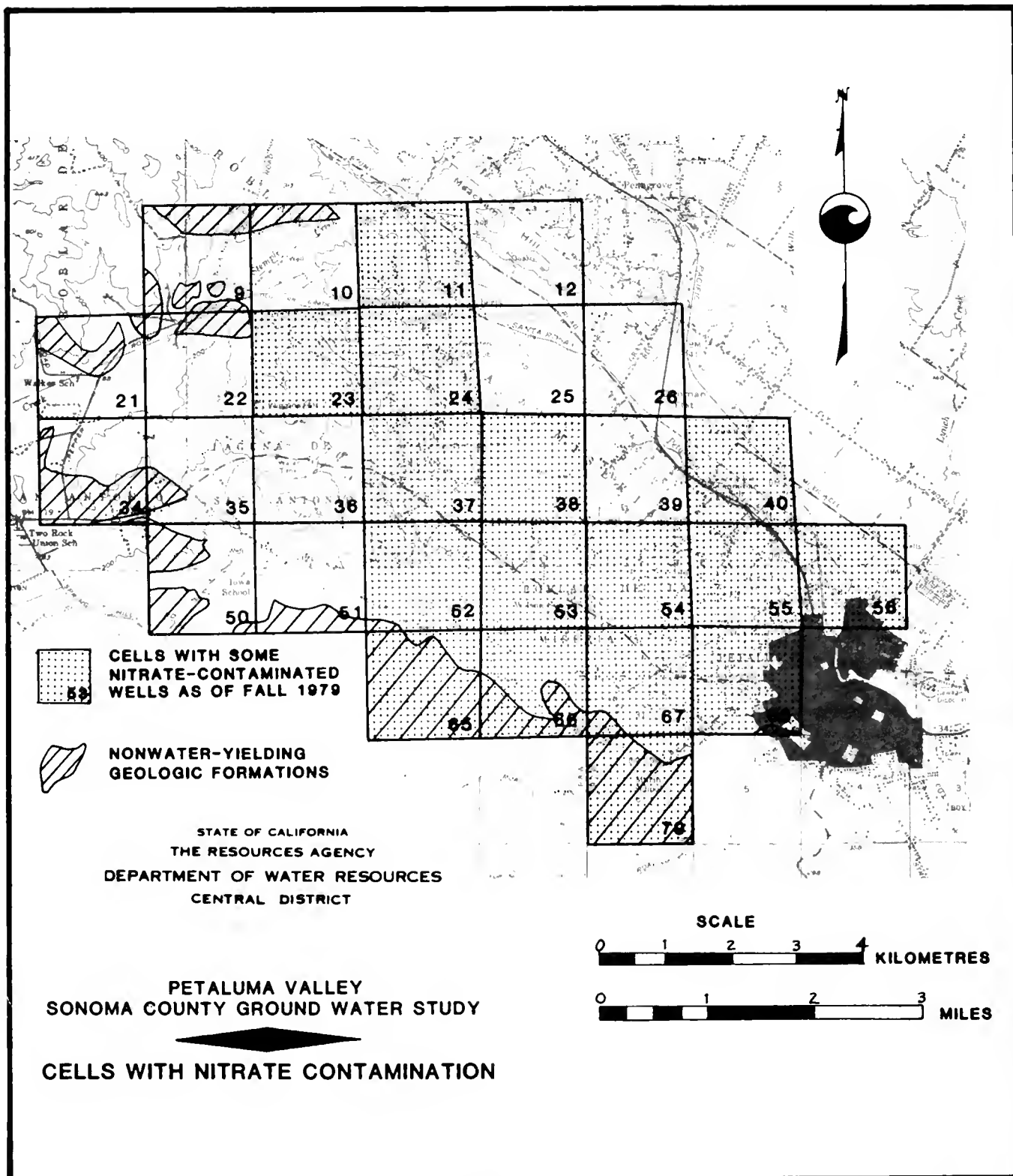


Table 3

PRESENT AND POSSIBLE FUTURE EXTENT OF NITRATE
CONTAMINATION OF GROUND WATER NORTHWEST OF PETALUMA

Time	Cells involved	Depth of contamination metres:(feet)	Volume of water extractible at present time/ cubic : deka- metres :	Volume of water extractible at present time/ (acre-feet)	Volume of water contaminated cubic : deka- metres :	Percent of water extract- ible at present affected
Present	<u>2/</u>	15	(50)	271 000	(220,000)	21 000 (17,000) 8
	<u>2/</u>	30	(100)	271 000	(220,000)	60 000 (49,000) 22
Future	<u>3/</u>	15	(50)	482 000	(391,000)	32 000 (26,000) 7
	<u>3/</u>	30	(100)	482 000	(391,000)	99 000 (81,000) 21

1/ Average well at present is 55 metres (180 feet) deep. These numbers represent the volume of water stored to this depth below land surface.

2/ Currently affected cells: 11, 23, 24, 37, 38, 52-56, 65-68, 79, southwestern half of 40.

3/ All currently affected cells plus nearby cells: 9, 10, 21, 22, 25, 34-36, 39, 50, 51, southwestern half of 12 and 26.

If ground water pumpage in this area does increase to historical levels without mitigating measures, saline water will probably migrate farther into ground water bodies that presently have acceptable water quality. This increased risk of intrusion is offset to some degree by increased indirect ground water recharge stemming from use of the imported water, which currently meets 85 percent of the water demand of Petaluma.

Further Limits on Volume of
Usable Ground Water

After subtracting the volume of water contaminated by nitrates and sea water from the total volume of ground water

in storage in the Petaluma Valley, there remains 1 642 300 dam³ (1,332,000 ac-ft) of usable ground water in storage as of fall 1980.

Experience has shown that not all this water can be extracted. Sustained yield is the volume of this total water in storage that can be extracted annually without causing adverse effects on the ground water basin. Sustained yield generally equals annual recharge to the basin, but can be increased over a short period of time to temporarily remove an additional volume of water beyond seasonal fluctuations. This dewatering creates storage space for additional capture and recharge of surface water during wet years.

The hydrologic balance of a ground water basin can be described by the hydrologic equation:

$$\text{Inflow} - \text{Outflow} = \text{Change in Storage}$$

The "inflow" term in this equation is the volume of water returned to the basin and the "outflow" term is the volume of ground water removed from the basin. The "change in storage" term represents the change in the volume of ground water in storage which, if greater than zero, is the accretion to ground water storage for that period.

To determine the natural recharge rate, and therefore the sustained yield of the basin, data are required that have not been collected in the Petaluma Valley:

1. The volume of water entering the ground water basin, which includes:
 - ° Volume of irrigation water that percolates to the ground water body (deep percolation).
 - ° Volume of streamflow and precipitation that percolates to the ground water body.
 - ° Volume of waste water that percolates to the ground water body.
2. The volume of water removed from the ground water basin, which includes:
 - ° Volume of ground water pumpage.
 - ° Volume of surface and subsurface water flowing out of the basin.
 - ° Volume of water used by vegetation (evapotranspiration).

This type of detailed balance was not attempted during this study because of the lack of data.

A rough estimate of the volume of annual recharge to the Petaluma Valley basin has been made using the computer program

TRANSCAP. The Petaluma Valley was divided in two, with cells 1-89 included in the northern portion and cells 90-132 included in the southern portion (Figure 7). The recharge estimate was made for the northern half of the valley because sea water intrusion limits the use of ground water contained in shallow aquifers in the southern portion. These shallow aquifers would normally provide storage for recharged water.

Hydrographs of wells in the northern half of the Petaluma Valley generally show an annual fluctuation of 3 m (10 ft) between spring and fall ground water level measurements. Based on TRANSCAP, this fluctuation represents a total volume of 50 000 dam³ (40,000 ac-ft) of ground water that is withdrawn and naturally recharged every year. Note that this value of recharge was calculated assuming that the ground water levels fluctuated a uniform 3 m (10 ft) in all cells in the northern Petaluma Valley; some wells east of Petaluma have annual fluctuations that average 1.5 m (5 ft).

This calculation also assumes that all ground water in the Petaluma Valley is unconfined, even though some areas in the Petaluma Valley are thought to have semi-confined to confined ground water (Cardwell, 1958). The portion of all ground water in the study area that is semiconfined to confined is not known. Confinement would reduce the volume of recharge determined from the 3-m (10-ft) fluctuation; the amount of reduction is not known. In determining the area to be included in the recharge calculation, some cells known to contain small amounts of fresh ground water were not included in the northern portion, and a few containing brackish water were included.

Hydrographs indicate that during the 1976-77 drought, ground water levels were lowered an average of 3 m (10 ft) below the normal low fall level. By spring 1978, most ground water levels returned to normal high spring levels. This 6-m (20-ft) change in ground water levels at the end of the 1976-77 drought represents

a total volume of 100 000 dam³ (80,000 ac-ft) of recharge if all ground water is unconfined. Therefore, the 50 000 dam³ (40,000 ac-ft) represents an approximate average volume of annual recharge in the northern Petaluma Valley. The 100 000 dam³ (80,000 ac-ft) of recharge after a time of unusually low ground water levels indicates that this area is capable of higher annual recharge if there were space in the aquifers to store it. Under present conditions, it appears that natural recharge exceeds the

storage capacity; the surplus runs off as "rejected recharge".

The northern Petaluma Valley appears to be capable of recharge that under normal conditions would fill the available storage capacity. There may, therefore, be a topographic limit to the volume of natural recharge that can be stored before "leakage" begins. If more than a certain volume of water is recharged, that stored water begins to leak out in creeks, roadcuts, and as springs.

CHAPTER 5. GROUND WATER MOVEMENT IN PETALUMA VALLEY

The effect of increased ground water extraction on the Petaluma Valley is a function of the degree to which aquifers are connected, including the presence or absence of barriers to ground water movement. Aquifer continuity controls the migration of poor quality ground water from one area to another and the extent to which sea water can move into freshwater aquifers. Aquifer continuity controls the degree of interaction between ground water and fresh surface water, and it influences the movement of naturally and artificially recharged water from a recharge site to an area of ground water extraction.

Aquifer Continuity

The degree of aquifer continuity is controlled by two factors: the areal extent of each single aquifer or group of interconnected aquifers, and the influence of faults on ground water. The areal extent of an aquifer or aquifers can be evaluated by examining the surficial and subsurface geology, reviewing ground water quality data to locate similar quality types, and comparing hydrographs for wells of different depths or in different locations. Faults can influence ground water by reducing or increasing transmissivity across the fault plane; the influence of faults on ground water movement can be determined from constant-rate pump tests of water wells and from ground water level maps.

The geology of the Petaluma Valley indicates that the water-yielding sands and gravels of the Merced Formation generally form continuous aquifers. Most of the other geologic units in the Petaluma Valley contain discontinuous lenses of water-yielding sands and gravels, while other units consist of nonwater-yielding material. These characteristics result

in a number of isolated ground water bodies, each having a unique water quality. These same characteristics also reduce the potential for vertical and horizontal movement of ground water. Ground water movement can be analyzed for local areas in the Petaluma Valley, but because of the number of isolated water bodies, some of which may be semiconfined, basinwide predictions of ground water behavior made with existing data are of questionable value.

To determine the areal extent of aquifers in the Petaluma Valley, standard mineral analyses of ground water were evaluated. Standard mineral analyses include the concentrations of the cations calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^{+}), and potassium (K^{+}), and the anions bicarbonate (HCO_3^{-}), carbonate ($\text{CO}_3^{=}$), sulfate ($\text{SO}_4^{=}$), and chloride (Cl^{-}).

In this report, water types are described by listing cations first, in order of abundance in milliequivalents per litre, followed by anions, in order of abundance. A single cation or anion is used to describe a water type if that ion constitutes over 50 percent of the total cations or anions in solution. Closely spaced wells with similar water quality types were assumed to tap the same aquifer. Conversely, it was assumed that aquifer separation exists to the degree that water quality types vary when taken from wells with perforations at the same elevation at different locations, or different elevations at the same location.

Ideally, ground water quality data collected entirely within a single year should be used to evaluate regional water quality because the chemical composition of ground water can change slowly over time. Water quality data for the Petaluma Valley are sparse and were

collected sporadically over 30 years. In some cases, several analyses have been collected for the same well. In determining regional ground water quality patterns, the most recent data have been given the most weight.

Wells pumping from the same aquifer, even wells of different depths or in different locations, usually will have similar water level fluctuations shown on well hydrographs. The few long-term hydrographs available for wells in the Petaluma Valley were examined for similarities and differences.

Aquifer continuity will be described by geologic units because each unit has distinct properties controlling the occurrence of ground water (see Plate 1 and Figures 5A-E).

Bay Mud Deposits

The few water-yielding zones present in the bay mud deposits generally lack vertical and horizontal continuity. Water in the bay mud deposits is generally brackish and of poor quality, and varies from magnesium chloride to sodium chloride.

The variation in water quality types indicates a lack of any significant aquifer continuity within the bay muds. No hydrographs are available for the few shallow wells that pump from bay mud deposits, so no evaluation of the aquifer continuity between bay muds and alluvial fan deposits can be made. Although the amount of aquifer continuity is assumed to be small, under heavy pumping in fan deposits, some brackish water may be drawn from bay mud deposits into the alluvial fans.

Alluvial Fan Deposits and Alluvium

Most aquifers within the alluvial fan deposits and alluvium are vertically continuous; these aquifers may be continuous with aquifers in underlying formations,

depending on the lithology of the underlying formations. The extent of horizontal continuity within these alluvial deposits is much more variable.

Northeast of Petaluma (cell 56) and south of Meacham Hill (cells 26 and 39), fan deposits are vertically continuous with the underlying Merced Formation. In cells 41 and 42 and in cell 58 east of Petaluma, there appears to be good vertical continuity between fan deposits and the underlying Petaluma Formation.

Lack of ground water quality data prevents a detailed analysis of horizontal and vertical continuity in the alluvial deposits in other areas. Because water quality data indicate sea water intrusion in some alluvial fan deposits near the Petaluma River, there must be some horizontal aquifer continuity in that area. In cell 71, there is a 15-m (50-ft) thick zone of unusually high chlorides 27 m (90 ft) below the land surface; the chlorides may be related to sea water intrusion. At some times in the past, under the stress of heavy ground water pumpage, sea water moved through the fans into the underlying formations in those areas where aquifers were vertically continuous.

A ground water elevation map of the study area was drawn based on fall 1980 water levels in shallow wells pumping from alluvial fan deposits and the Merced Formation (Figure 10). Water levels in wells pumping from both the alluvial fan deposits and underlying materials were not used, because these levels are generally lower and more variable than levels in wells drawing only from fan deposits. Ground water levels in these deeper wells may actually represent the piezometric surface of a confined or semiconfined aquifer.

Merced Formation

The Merced Formation in the hills west of Petaluma produces water of a distinctly

different quality type than the Merced beneath the valley floor to the east. Water in the hills is generally a calcium bicarbonate chloride type regardless of well depth. Two shallow wells in cell 40, which draw from alluvial fan deposits and the Merced Formation, produce a poor quality calcium chloride water (5N/7W-20L2 and -20L3); this unusual quality may be a result of surface contamination. In general, there appears to be good horizontal and vertical aquifer continuity within the western hills. Impermeable flows from the Sonoma Volcanics locally separate the lower reduced Merced Formation from the upper oxidized Merced.

Beneath the valley floor east of Petaluma, the Merced Formation generally contains sodium bicarbonate water. Some isolated water bodies contain chloride ion (cell 26). Some wells in cell 40 (such as 5N/7W-20B1) produce water midway in quality between the Merced of the hills and the Merced beneath the valley floor near Petaluma -- higher calcium and chloride concentrations than the Merced near Petaluma and higher sodium and bicarbonate concentrations than the Merced in the hills. This indicates some degree of aquifer continuity between the two areas, allowing mixing of ground water. Aquifer separation across the Meacham Hill fault trace is suggested by differences in water quality type between 200-m (600-ft) wells 0.8 kilometre (0.5 mile) apart on either side of the fault trace; well 5N/7W-20B1 (cell 40) produces a sodium calcium chloride bicarbonate water, and well 5N/7W-16N1 (cell 28) produces a sodium bicarbonate water.

Petaluma Formation

The Petaluma Formation has variable water quality and degrees of aquifer continuity. Since the Petaluma is a marine formation, it frequently contains

brackish connate water that is highly mineralized.

At the southern end of the Petaluma Valley there is a zone of poor quality connate water at least 50 m (150 ft) below the land surface that extends vertically to a depth of at least 210 m (700 ft). The zone extends horizontally from cell 128 north at least to cell 113, based on existing water quality data. Since the geology indicates few if any aquifers in this area, the poor water quality is probably a result of sea water trapped in the fine-grained sediments as they were deposited.

In the Sonoma Mountains on the eastern boundary of the study area, the quality of ground water varies greatly depending on the volume of connate water remaining in the Petaluma Formation. In 1958, Cardwell described well 5N/7W-24F1 (576 m or 1,896 ft deep) as contaminated by connate water, and nearby well 5N/7W-25C1 (72 m or 235 ft deep) as flushed of connate water (Plate 4); well 5N/7W-25C1 has much lower levels of boron, salinity, and total dissolved solids. Wells 5N/6W-30D1 (47 m or 155 ft deep) and 5N/7W-25C1 are of similar depth but different water quality; well 5N/7W-25C1 has much lower levels of salinity and total dissolved solids and has sulfate instead of chloride as its second most abundant anion. These data suggest that there is little aquifer continuity vertically or horizontally within the Petaluma Formation in this area.

The Petaluma Formation near Petaluma generally contains bicarbonate ground water with varying percentages of calcium, magnesium, and sodium. It appears that the Petaluma Formation is connected with near-surface deposits in cell 58 because a 120-m (400-ft) well in that cell fluctuates with tidal loading (Cardwell, 1958). Data are insufficient to further evaluate vertical or horizontal aquifer connection in this area.

Other Geologic Units

Because of the variable geology of the Tolay and Sonoma Volcanics, it was not possible to determine the extent of aquifer continuity within their permeable units. The Franciscan complex in the Petaluma Valley contains water only in fractures; the amount of continuity depends on the extent those fractures are connected. The extent of fracture interconnection was not determined.

Faults

There are several ways to determine the effect of faults on ground water movement. During a 24-hour constant-rate water well pump test, the apparent transmissivity of the aquifer will drop abruptly when the well's pumping cone intercepts a fault acting as a barrier. Unfortunately, few long constant-rate pump tests are available in the Petaluma Valley. Ground water level maps are drawn from measurements taken in wells of known depth and construction. Water level contours in general reflect topography but can be influenced by barriers such as faults that reduce ground water flow.

Reduced transmissivity across faults causes water to "stack up" on the side of the fault nearest the source of recharge. A ground water level map for fall 1980 (Figure 10) indicates that ground water levels steepen in the vicinity of the Meacham Hill fault trace. This may reflect the fault's influence on near-surface water-yielding deposits. The Cinnabar School fault does not appear to influence ground water levels. The southern portion of the Tolay fault influences ground water levels by bringing nonwater-yielding material to the surface along the western side of the fault trace.

Sea Water Intrusion

In the past, sea water intrusion has degraded the few aquifers present in bay mud deposits and aquifers in the alluvial fan deposits in the Petaluma Valley. In 1958, Cardwell described inland movement of sea water from the tidal reach of the Petaluma River into alluvial fan deposits near the City of Petaluma. The limited water quality data collected since 1958 indicate that ground water quality in this area has not deteriorated further since delivery of surface water to the City of Petaluma began in 1962 because the volume of municipal ground water pumpage has been reduced. Increasing ground water pumpage to 1961 levels or beyond might again create an inland gradient and renew sea water intrusion.

The extent of sea water intrusion in the bay mud deposits in the southern Petaluma Valley is more difficult to determine. The bay muds were originally deposited in a marine environment, and much sea water was trapped in the fine-grained sediments at that time. In general, little fresh water has moved through the deposits since deposition, so the deposits contain highly mineralized, brackish water. In addition, some wells (such as 4N/6W-7H2) near the tidal reach of the Petaluma River produce magnesium and sodium chloride water even closer to the composition of sea water, as a result of post depositional inland sea water movement. Because these deposits are fine-grained, water moves through them slowly, and the movement of sea water into the deposits should remain a localized phenomenon. Because of the generally poor quality of water in the bay mud deposits, water contained in these deposits was not included in estimates of the volume of usable ground water in the Petaluma Valley (Chapter 4).

Natural and Artificial Recharge

Recharge is the movement of water from land surfaces and streambeds into underlying aquifers. Because aquifers in the Petaluma Valley are generally full at present, recharge occurs in response to natural subsurface outflow or pumpage of ground water from those aquifers. Several physical factors control natural recharge in an area:

- ° Slope of the land surface.
- ° Permeability of the soils.
- ° Subsurface geology.
- ° Amount of available storage space in the aquifer.

A rough estimate of the annual volume of natural recharge is presented in Chapter 4.

For recharge to take place in an area, the slope of the land surface should be less than 15 percent and the infiltration rate of the soil profile should exceed 1.5 centimetres (0.6 inch) per hour (Muir and Johnson, 1979). If the slope is greater than 15 percent, rapid runoff greatly reduces the recharge potential. For an appreciable amount of water to penetrate the soil, the infiltration rate must be rapid.

Subsurface geology is an important factor in evaluating a recharge area and is the most difficult factor to evaluate. Good aquifer continuity between the area of recharge and the area of extraction is necessary. The extent of aquifer continuity in the Petaluma Valley has already been discussed at the beginning of this chapter. The extent to which the Cinnabar School and Meacham Hill faults affect ground water movement has not been determined. The ground water level measurement network now being implemented by the Department of Water Resources and the Sonoma County Water Agency will provide more information on the continuity of aquifers. Other data that would aid in determining water movement would be:

- ° 24-hour constant-rate pump tests to determine aquifer transmissivity.
- ° Drilling at potential artificial recharge sites to determine detailed local subsurface geology.

The availability or the lack of storage space in the aquifer determines whether or not recharge can take place.

Without available storage space in the underlying aquifer, surface water will run off even the most favorable recharge site as "rejected recharge". Figure 7 shows areas of favorable slope and soils within the study area and estimates of available storage as of fall 1980 in aquifers within each cell.

Soils with slopes and permeabilities suitable for natural and artificial recharge cover 4 500 hectares (11,000 acres) in the Petaluma Valley study area -- 18 percent of the total land surface (Figure 7). An additional 400 hectares (900 acres) are covered by soils of suitable permeability; they can be classified as recharge areas if the land slope is less than 15 percent.

The largest concentration of suitable soils is northwest of the City of Petaluma. These soils have formed on the sandy Merced Formation and cover 28 percent of the land surface in this area. Many soils in this area not classified as recharge areas were excluded because land slope exceeded 15 percent. If runoff were controlled by modifications of slopes, construction of ponds, or other methods, recharge to the ground water body could be increased. The Merced Formation in this area is essentially one continuous aquifer averaging 150 m (450 ft) in thickness.

Because few creeks cross the recharge areas, the major source of natural recharge to the Merced Formation appears to be from rain falling on suitable soils. The rate of recharge from

rainfall is generally slow, depending on the annual precipitation. This suggests that if long-term draft on the ground water in this area were heavy, ground water recharge could not keep pace. Water levels did recover rapidly from the 2-year 1976-1977 drought; a 50-m (180-ft) deep well in cell 39 (5N/7W-19N1) had recovered 6 m (20 ft) to predrought levels by spring 1978.

Other recharge areas dot the western uplands. Soils suitable for recharge underlie portions of the City of Petaluma, having formed on top of a thin deposit of alluvium and, to a lesser extent, alluvial fan deposits and the Tolay Volcanics.

The Petaluma River flows across some of these recharge areas; because there is little storage available in aquifers beneath these recharge areas, the loss of surface water to the ground water body is probably small. In fact, Cardwell reported in 1958 that water levels in streams in the Petaluma Valley, including the Petaluma River, generally stood lower than the water levels in nearby wells, indicating that the flow of ground water was maintaining streamflows. There are not sufficient recent shallow ground water level data available to compare stream and ground water levels at the present time. If the draft on the ground water body in these areas were to increase, thereby creating additional storage, the loss of surface water could increase proportionately. Because the Petaluma River is tidal and brackish at the City of Petaluma, an increase in river recharge in this area would not be desirable.

The degree to which increased pumping in areas away from the Petaluma River will increase available storage in the aquifers beneath the river and therefore increase river recharge is variable. It depends on the degree of aquifer connection between the two areas and on the presence or absence of barriers, such as faults. Because there are no stream gaging stations operating on the Petaluma

River, there is no way to determine the amount of surface water lost from the river due to percolation to the ground water body. Stations would have to be installed on the Petaluma River to determine losses in the future.

Recharge areas are scattered on the western flank of the Sonoma Mountains, generally forming on the Sonoma Volcanics. As in the western uplands, most recharge is from rainfall because few streams flow across recharge areas. The fate of the recharged water is difficult to determine because of the discontinuous nature of aquifers in the Sonoma Volcanics.

Aquifers beneath the valley floor are recharged less directly than those aquifers overlain by recharge areas. While infiltration from rainfall and streamflow still occurs, the rate is much slower.

In mountainous areas, recharge from rain or streams occurs when an aquifer is exposed at the surface. Recharged ground water then moves down dip in the aquifer (Figure 13) until:

- ° The water reaches the lowest point in elevation, where it remains because the gradient is zero.
- ° The aquifer again is at the land surface, where ground water is released as a spring.
- ° Ground water encounters a barrier, which can reduce the flow rate or create a spring.

When aquifers are as discontinuous as those in the mountainous portions of the study area, ground water frequently does not reach the area of ground water extraction because of these geologic complexities.

At present, artificial recharge is not necessary in the Petaluma Valley because the ground water reservoir is essentially full and because surface water is available to meet most domestic needs. When

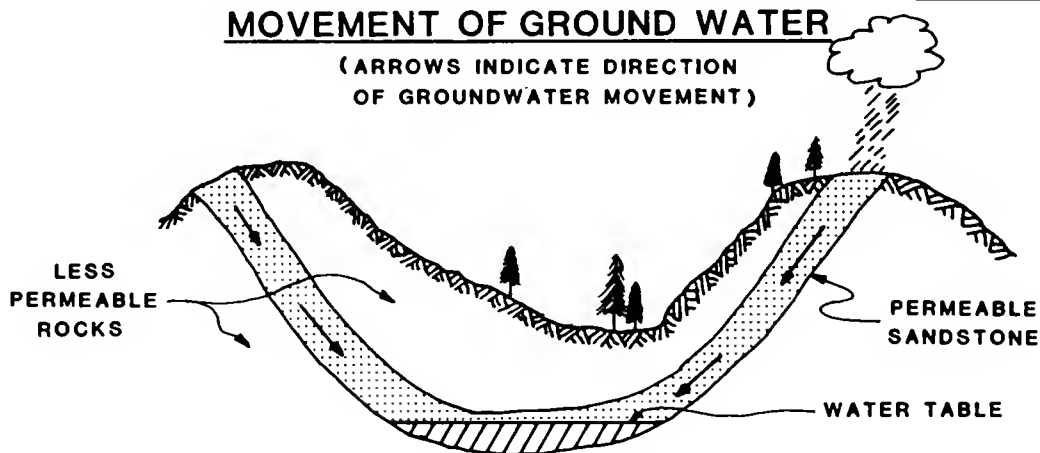
the reservoir has been dewatered sufficiently to make an artificial recharge program feasible, the recharge site(s) selected should be in an area of favorable slope and soil permeability. A detailed subsurface geologic investigation should be conducted for the proposed site, including on-site drilling and evaluation of the degree of connection between the recharge area and the area of

extraction. Although the area northwest of Petaluma contains many potential recharge sites, care should be taken to avoid moving nitrate-contaminated ground water into presently unaffected areas. In the valley area near Petaluma, an artificial recharge program to halt or reverse sea water intrusion should be considered if further water quality sampling indicates renewed inland movement of sea water.

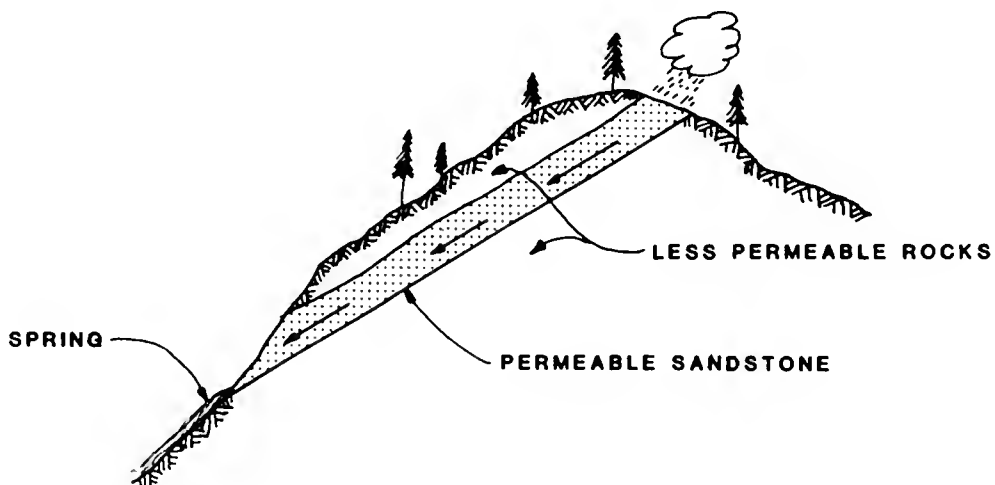
FIGURE 13

MOVEMENT OF GROUND WATER

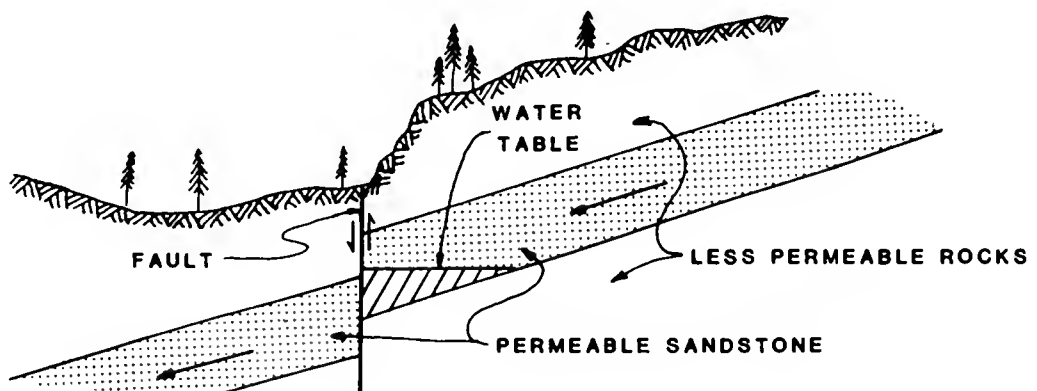
(ARROWS INDICATE DIRECTION
OF GROUNDWATER MOVEMENT)



GROUND WATER MOVES DOWNDIP
UNTIL IT REACHES THE LOWEST POINT IN ELEVATION



GROUND WATER MOVES DOWNDIP UNTIL
THE PERMEABLE ROCKS ARE AGAIN AT THE SURFACE
GROUND WATER IS RELEASED AS A SPRING



TRANSMISSIVITY IS REDUCED ACROSS FAULT
GROUND WATER "STACKS UP" ON UPHILL SIDE OF FAULT

CHAPTER 6. SOURCE AND POTENTIAL MIGRATION OF SELECTED MINERAL CONSTITUENTS

Many ions and substances, when present above certain concentrations in ground water, can be harmful to humans, animals, or plants. Increased ground water pumpage near areas with ground water quality problems may cause the ground water containing these constituents to migrate.

Summary

Sodium, salinity, total dissolved solids (TDS), boron, nitrate, hardness, and iron and manganese concentrations in ground water were examined during this study. High sodium, salinity, TDS, and boron frequently occur together, most commonly in wells affected by sea water intrusion or in connate water of marine origin.

High nitrate levels are widespread in ground water in the area northwest of Petaluma as the result of contamination from surface sources. Elevated electrical conductivity (EC) levels in this area may be a result of surface contamination, connate water stored near the base of the Merced Formation, or a combination of these factors.

Hard to moderately hard water is common throughout the Petaluma Valley; hard water is found in wells affected by sea water or wells that tap connate waters of marine origin.

Few accurate analyses are available for iron and manganese; available data indicate that water containing iron and manganese above recommended limits is produced from wells:

- ° Tapping alluvial fan deposits.
- ° Tapping the Petaluma Formation.
- ° Tapping the Sonoma Volcanics.

The potential for movement of ground water with these quality problems varies. There is a high potential for migration of nitrate-contaminated water in the area northwest of the City of Petaluma. There is a low potential for migration of poor quality ground water in the lower Petaluma Valley because the sediments containing the ground water are fine-grained.

Aquifers in the central and northern part of the Petaluma Valley are connected in some areas; in the past, sea water has moved inland under the stress of increased pumpage. Water quality degradation caused by intrusion may include increased sodium, salinity, TDS, boron, hardness, and iron and manganese. Periodic monitoring should be conducted near wells with water quality problems in areas conducive to ground water migration.

Some quality problems could not be evaluated because data were insufficient. Hydrogen sulfide has been noted in a Petaluma municipal well in cell 42 (Condiotti well, 5N/7W-22Q). High temperature is sometimes associated with hydrogen sulfide. No further analyses of these problems have been made.

The pumping of large amounts of sand by water wells can be a serious problem; sand damages the pump and fills in the well casing. Many of the Petaluma municipal wells pump sand; one 120-m (400-ft) well in cell 58 was abandoned due to excessive sanding (well 5N/7W-26R1). The sand causing the problem is probably related to a very fine sand present in the Merced Formation that may be eroded and redeposited as part of the alluvial fan deposits. Only careful well design using a small slot size and a

fine-grained gravel pack will prevent this sand from entering the well during pumping. No further information on the extent of the sanding problem in the Petaluma Valley is available.

Sodium

High concentrations of sodium ion may be hazardous to persons with heart problems, such as high blood pressure. While generally not hazardous to livestock, high concentrations of sodium ion can adversely affect agriculture by causing soils to deflocculate or "puddle"; a hard crust forms after irrigating, adversely affecting tilth, permeability, and infiltration.

Based on the University of California Committee of Consultants report, "Guidelines for Interpretation of Water Quality for Agriculture" (Ayers and Branson, 1975), the adjusted sodium adsorption ratio (ASAR) is used to evaluate the effect of sodium on agriculture. The ratio is computed by the following formula:

$$ASAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \left[1 + (8.4 - pH_C) \right]$$

where pH_C is a calculated value based on the water analysis for total salinity ($Na+Ca+Mg$), on the calcium and magnesium ($Ca+Mg$), and on the carbonates and bicarbonates (CO_3+HCO_3), all expressed in milliequivalents per litre (see Ford, 1975, Table 20).

For ion toxicity from root absorption, problems increase as the ASAR exceeds 3; severe problems occur when the ASAR is greater than 9 (Ayers and Branson, 1975). For ion toxicity from foliar absorption, problems increase as the ASAR exceeds 3. Foliar absorption limits are important when sprinklers are used for irrigation or frost control. Previous guidelines for sodium used the SAR rather than the ASAR. The new guidelines (ASAR) recommend a lower concentration of sodium than the previous guidelines.

Of 61 wells analyzed for sodium in the Petaluma Valley, 42 were found to have ASAR values exceeding 3; 18 have ASAR values exceeding 9 (Table 4 and Figure 14A). Of the 42 wells, 8 had been similarly identified in DWR Bulletin 118-4, Volume 1 (Ford, 1975), using Hem. Water from the affected wells does not represent a single quality type, although sodium is generally the dominant cation.

The highest sodium is in the southern portion of the Petaluma Valley in water from aquifers that have been intruded by sea water and in connate waters trapped in the Petaluma Formation. High sodium is already widespread in this area; because the sediments are fine-grained, the potential for migration is low except within coarser grained alluvial fan deposits that have been intruded. The possibility of movement is high in the intruded fan deposits if the sea water intrusion is allowed to spread.

Water from wells in the uplands on the eastern side of the Petaluma Valley have severe sodium problems. The poor quality connate water is contained in isolated aquifers, and the potential for migration is low.

Water from a number of wells producing from the Petaluma Formation beneath the valley floor poses a severe sodium problem. The poor quality may be the result of connate water or of base exchange within clays, which increases the sodium concentration and decreases the calcium and magnesium concentrations. There is a potential for migration into overlying alluvial deposits because there is some vertical aquifer connection in this area. Likewise, the Merced Formation beneath the valley floor contains water with a moderate sodium concentration that may migrate vertically.

Salinity

Excessive salinity in water can kill sensitive plants and impart a salty taste to drinking water. The degree of

Table 4
SODIUM IN GROUND WATER
IN EXCESS OF RECOMMENDED STANDARDS

Well Number	Depth		Date of	Adjusted	Degree of	Hazard
	metres	(feet)	Sampling mo/yr	SAR Value ^{1/}	Increas- ing	Severe
3N/5W-06C01	15	(50)	8/58	7.3	x	
3N/6W-01Q01	69	(225)	4/62	50.63/		x
-03C01	--	(--)	4/63	13.82/		x
-11B01	76	(250)	3/65	22.32/		x
-11L01	159	(520)	6/75	16.0		x
4N/6W-07H01	11	(35)	8/58	5.6	x	
-07H02	--	(--)	3/59	42.32/		x
-08E01	23	(74)	8/59	4.6	x	
-21A01	79	(259)	8/72	3.3	x	
-21Q01	141	(464)	4/63	21.42/		x
-27N01	68	(222)	3/59	11.2		x
-27R01	224	(736)	3/65	12.4		x
-33R01	53	(175)	3/65	30.72,4/		x
4N/7W-02D01	19	(62)	3/65	38.42/		x
5N/6W-30D01	47	(155)	8/78	11.4		x
5N/7W-08D01	--	(--)	5/47	7.2	x	
-08D03	42	(138)	4/63	4.2	x	
-16N01	184	(605)	12/58	7.6	x	
-18P	182	(597)	7/77	4.5	x	
-19A01	99	(325)	3/59	4.7	x	
-19A	182	(596)	9/77	4.1	x	
-20B01	183	(600)	5/47	8.3	x	
-20C01	210	(688)	3/59	3.2	x	
-20L02	19	(62)	3/59	3.2	x	
-20L03	15	(50)	3/65	5.1	x	
-24B01	198	(650)	9/49	52.0		x
-24F01	578	(1,896)	10/50	16.5		x
-25C01	72	(235)	5/47	9.55/		x
-26E01	184	(605)	8/78	6.5	x	
-26R01	130	(428)	2/49	6.2	x	
-27A01	130	(425)	3/59	3.3	x	
-28A01	153	(502)	7/49	7.5	x	
-28A03	85	(280)	9/59	7.7	x	
-28H05	143	(468)	5/49	7.6	x	
-28N01	19	(62)	3/58	6.6	x	
-33N01	91	(300)	8/58	6.0	x	
-33Q01	63	(205)	8/58	3.6	x	
-34A01	125	(410)	6/49	9.6		x
-34A02	159	(520)	8/50	11.6		x
-34E02	85	(280)	3/65	23.6 2/		x
-34G01	70	(230)	3/54	9.5		x
-34G02	85	(280)	9/60	24.1 2/		x
-35H01	165	(542)	7/49	5.1	x	
-35L	70	(229)	5/77	4.5	x	

^{1/} All exceed recommended limit of ASAR = 3. Sodium hazard rates "severe" if ASAR >9.

^{2/} Well described in DWR Bulletin 118-4, Volume 1 (Ford, 1975).

^{3/} ASAR was 16.5 in 6/76.

^{4/} ASAR was 14.3 in 7/68.

^{5/} ASAR was 5.3 in 9/59.

salinity hazard is different for agricultural and domestic water supplies. Salinity of both agricultural and domestic water supplies is measured by electrical conductivity and chloride ion concentration.

In agriculture, salinity problems from root absorption are related to electrical conductivity (EC). Problems increase as the EC exceeds 750 microsiemens per centimetre (uS/cm). Problems are severe when the EC exceeds 3 000 uS/cm.

A related problem in agriculture is ion toxicity caused by high levels of chloride ion. Problems from foliar absorption increase as the chloride ion concentration exceeds 106 milligrams per litre (mg/L). Problems from root absorption increase as the chloride ion concentration exceeds 142 mg/L; problems are severe when the concentration exceeds 355 mg/L (Ayers and Branson, 1975).

The salinity of domestic water supplies is measured by the content of chloride ion and electrical conductivity. Title 22 of the California Administrative Code (California Department of Health, 1977) recommends a maximum concentration of chloride ion in drinking water of 250 mg/L; the maximum allowable concentration is 500 mg/L. Water containing more than 250 mg/L of chloride ion usually has a noticeably salty taste. The maximum recommended electrical conductivity for drinking water is 900 uS/cm. The upper limit for EC is 1 600 uS, although for short periods of time, water with EC values up to 2 200 uS/cm can be used.

Of the 269 wells evaluated in the Petaluma Valley, 130 produce water with an EC greater than 750 uS/cm; 6 exceed 3 000 uS/cm. Of the 69 wells tested for chloride ion, 31 produce water with chloride ion concentrations greater than 106 mg/L and 21 exceed 142 mg/L; 12 exceed 250 mg/L and 7 exceed 500 mg/L (Table 5 and Figure 14B).

In the Petaluma Valley, ground water with a high EC is generally found in areas affected by sea water intrusion into shallow aquifers or by connate water trapped within fine-grained sediments of the Petaluma Formation. In the hills west of Petaluma, the normal EC may have been locally increased by contamination from surface leachate. In the hills west of Petaluma, EC values also increase as the base of the Merced Formation is approached. The base of the formation is near contacts with the Franciscan complex or Tolay Volcanics, and is generally west of the City of Petaluma. The basal portion of the Merced Formation was not as completely flushed with fresh water after its marine deposition as were the middle and upper portions of the formation; the remaining connate water has a high EC, usually greater than 900 uS/cm, and occasionally as high as 3 000 uS/cm (Ford, in progress).

Chloride ion concentrations exceeding recommended limits generally result from sea water intrusion, although chloride ion is common in water from the Merced Formation northwest of Petaluma, where chloride concentration decreases with depth, and in the Petaluma Formation on the east side of the study area. Within the alluvial fan deposits in cell 71, there is a 15-m (50-ft) thick zone of unusually high chlorides 27 m (90 ft) below land surface; the chlorides may be related to sea water intrusion.

Chloride ion concentration is generally very low in water from alluvial fan deposits or alluvium when these deposits are not intruded by sea water. Two shallow wells in cell 40 (wells 5N/7W-20L2 and -20L3) produce water with both high electrical conductivity and high chloride ion concentration; the source may be surface contamination.

The potential for migration of water known to have high salinity is greatest in the Merced Formation and alluvial fan deposits. Although the extent of sea water intrusion has remained the same or decreased over the past 20 years, this

Table 5

SALINITY OF GROUND WATER IN EXCESS OF RECOMMENDED STANDARDS

Well Number	Depth metres (feet)	Date of sam- pling mo/yr	Chloride ion concen- tration mg/L	Elec- trical conduc- tivity ^{1/} µS/cm	Well Number	Depth metres (feet)	Date of sam- pling mo/yr	Chloride ion concen- tration mg/L	Elec- trical conduc- tivity ^{1/} µS/cm
3N/5W-06C01	15 (50)	4/52	147	1 270	5N/7W-30K08	-- (--)	10/79	---	870
3N/6W-01Q01	69 (225)	4/62	150	1 370	-30K09	-- (--)	10/79	---	1 190
-03C01	-- (--)	3/65	4 241	11 000	-30K10	-- (--)	10/79	---	942
-11B01	76 (250)	3/58	304	2 120	-30K12	-- (--)	10/79	---	1 070
-11L01	159 (520)	8/79	471	2 060	-30K13	-- (--)	10/79	---	1 140
4N/6W-07H01	11 (35)	9/66	55	1 230	-30L03	37 (122)	10/79	---	957
-07H02	-- (--)	3/59	1 360	5 260	-30M01	-- (--)	9/79	---	1 210
-08E01	23 (74)	8/77	123	1 260	-30M02	-- (--)	9/79	---	1 080
-21A01	80 (259)	8/78	244	1 290	-30N03	-- (--)	9/79	---	780
-21Q01	141 (464)	8/58	264	1 490	-30N05	-- (--)	9/79	---	800
-27N01	68 (222)	9/60	152	1 119	-30N10	-- (--)	9/79	---	975
-27R01	224 (736)	8/58	156	1 210	-30N11	-- (--)	10/79	---	829
-33R01	48 (175)	6/74	4 150	11 700	-30Q02	40 (130)	9/79	---	1 090
4N/7W-02D01	19 (62)	11/65	10 200	26 900	-30Q03	-- (--)	9/79	---	830
-04F01	56 (184)	8/58	143	1 280	-30Q04	-- (--)	9/79	---	917
-06B01	-- (--)	10/79	---	903	-30Q05	-- (--)	10/79	---	1 790
-06C01	-- (--)	10/79	---	1 803	-30Q06	-- (--)	10/79	---	851
-06G01	-- (--)	10/79	---	3 110	-30Q07	-- (--)	10/79	---	947
5N/6W-30D01	47 (155)	9/64	176	1 510	-30R06	-- (--)	9/79	---	846
5N/7W-08D01	-- (--)	5/47	112	910	-31A05	-- (--)	10/79	---	805
-08D03	42 (138)	4/62	177	1 100	-31A06	-- (--)	10/79	---	957
-10Q01	141 (462)	8/51	55	2 700	-31B01	-- (--)	9/79	---	1 970
-20B01	183 (600)	7/58	176	891	-31B02	-- (--)	9/79	---	813
-20C01	210 (688)	8/58	202	988	-31B04	-- (--)	9/79	---	927
-20L02	19 (62)	4/60	590	2 370	-31B05	35 (115)	9/79	---	980
-20L03	15 (50)	7/60	556	2 191	-31B06	-- (--)	9/79	---	1 120
-20N01	-- (--)	10/79	---	1 070	-31D01	-- (--)	10/79	---	1 330
-20N02	-- (--)	10/79	---	825	-31G01	-- (--)	9/79	---	812
-20N03	-- (--)	10/79	---	920	-31G03	-- (--)	10/79	---	855
-20N04	-- (--)	10/79	---	960	-31J01	-- (--)	10/79	---	882
-20N05	-- (--)	10/79	---	1 350	-31M01	-- (--)	10/79	---	1 440
-20P03	-- (--)	10/79	---	926	-31M02	-- (--)	10/79	---	979
-20P04	-- (--)	10/79	---	814	-31M03	-- (--)	10/79	---	1 600
-24B01	198 (650)	9/49	1 050	7 500	-31P01	-- (--)	10/79	---	2 140
-24F01	578 (1,896)	10/50	140	1 100	-31P02	-- (--)	10/79	---	1 020
-25A01	81 (265)	4/51	135	1 250	-31Q01	-- (--)	10/79	---	938
-26E01	184 (605)	8/74	86	842	-31R01	-- (--)	10/79	---	1 510
-28N01	19 (62)	8/58	247	1 620	-32D01	-- (--)	9/79	---	1 260
-29C01	-- (--)	9/79	---	891	-32M01	-- (--)	10/79	---	914
-29D01	-- (--)	9/79	---	912	-33Q01	63 (205)	3/59	92	961
-29D02	-- (--)	9/79	---	1 420	-34A01	125 (410)	6/49	128	909
-29D03	-- (--)	9/79	---	857	-34A02	159 (520)	8/51	255	1 130
-29D04	-- (--)	10/79	---	1 370	-34E02	85 (280)	7/68	68	908
-29D05	-- (--)	10/79	---	949	-34G01	70 (230)	8/54	425	1 770
-29D06	-- (--)	10/79	---	1 380	-34G02	85 (280)	9/60	76	854
-29D07	-- (--)	10/79	---	1 280	-35L	70 (229)	6/77	100	800
-29L01	20 (65)	2/50	100	960	5N/8W-01Q01	55 (180)	2/50	133	981
-29M02	73 (238)	10/79	---	1 030	-11N01	83 (271)	2/50	130	974
-29N01	74 (244)	3/59	138	1 000	-11R01	91 (300)	10/79	---	983
-29N02	-- (--)	9/79	---	1 160	-13N03	59 (192)	10/79	---	823
-29N03	44 (144)	9/79	---	819	-14L01	61 (200)	10/79	---	768
-29N05	-- (--)	9/79	---	936	-23D01	-- (--)	10/79	---	894
-30A01	36 (118)	10/79	---	933	-23R01	-- (--)	10/79	---	1 350
-30A03	-- (--)	10/79	---	1 280	-25K01	-- (--)	10/79	---	821
-30D02	-- (--)	10/79	---	988	-25Q01	-- (--)	10/79	---	1 230
-30D03	-- (--)	10/79	---	844	-26A01	59 (195)	10/79	---	1 590
-30E02	57 (188)	10/79	---	968	-26J01	-- (--)	10/79	---	1 360
-30E03	-- (--)	10/79	---	1 120	-26J02	-- (--)	10/79	---	916
-30E04	-- (--)	10/79	---	1 040	-35A01	-- (--)	10/79	---	840
-30E05	-- (--)	10/79	---	837	-36C01	-- (--)	10/79	---	899
-30E06	-- (--)	10/79	---	810	-36C03	-- (--)	10/79	---	1 560
-30G02	-- (--)	10/79	---	791	-36C04	82 (269)	10/79	---	1 750
-30H02	-- (--)	9/79	---	826	-36D01	61 (200)	10/79	---	1 000
-30H03	-- (--)	9/79	---	1 180	-36E01	-- (--)	10/79	---	1 010
-30H04	-- (--)	10/79	---	1 020	-36E02	-- (--)	10/79	---	1 340
-30J01	42 (138)	9/79	---	1 210					

^{1/} Electrical conductivity exceeds 750 µS (increasing problems, agriculture-root absorption).

Limits for chloride ion concentration:

- exceeds 250 mg/L (recommended limit, human drinking water)
- exceeds 106 mg/L (increasing problems, agriculture-foliar absorption)
- between 142-355 mg/L (increasing problems, agriculture-root absorption)
- exceeds 355 mg/L (severe problems, agriculture-root absorption)

could change with increased ground water pumpage, which could create a landward gradient and draw sea water inland. If ground water pumpage were to increase near aquifers intruded by sea water, salinity would then increase as sea water moves inland. If the City of Petaluma were to increase ground water pumpage to its 1961 levels (it presently pumps half that volume), sea water intrusion would probably resume.

Total Dissolved Solids

The amount of total dissolved solids (TDS) in water indicates the total mineral content in the water. The recommended limit for TDS in domestic water is 500 mg/L. The maximum limit for TDS is 1 000 mg/L, although for short periods of

time 1 500 mg/L is allowed (California Department of Health, 1977). Water with a TDS higher than 500 mg/L may also be expected to contain other hazardous ions, usually high sodium and salinity.

Of the 62 wells evaluated for TDS in the Petaluma Valley, 32 produce water with TDS greater than 500 mg/L; 10 of these exceed 1 000 mg/L (Table 6 and Figure 14C). Each of these wells also produces water that exceeds recommended limits for salinity, and most produce water that exceeds recommended limits for sodium and boron. The source of the poor quality water is similar to the source of salinity and is usually related to sea water intrusion or connate water. Potential for movement is the same as that for highly saline water.

Table 6

TOTAL DISSOLVED SOLIDS (TDS) IN GROUND WATER IN EXCESS OF RECOMMENDED STANDARDS

Well Number:	Depth	Date	TDS	Well Number:	Depth	Date	TDS		
:metres:(feet):	:metres:(feet):	: mo/yr :	: mg/L*	:metres:(feet):	:metres:(feet):	: mo/yr :	: mg/L*		
3N/5W-06C01	15	(50)	8/58	678	5N/7W-08D03	42	(138)	3/59	599
3N/6W-01Q01	69	(225)	4/62	811	-10Q01	141	(462)	8/51	1 473
-03C01	--	(--)	9/60	2 288	-20B01	183	(600)	7/58	584
-11B01	76	(250)	10/60	1 553	-20C01	210	(688)	4/61	572
-11L01	159	(520)	8/79	829	-20L02	19	(62)	9/59	1 320
4N/6W-07H01	11	(35)	4/63	671	-20L03	15	(50)	4/61	1 160
-07H02	--	(--)	3/59	3 060	-24B01	198	(650)	9/49	4 301
-08E01	23	(74)	8/79	666	-24F01	578	(1,896)	10/50	635
-21A01	79	(259)	8/72	699	-28N01	19	(62)	8/58	1 000
-21Q01	141	(464)	8/51	826	-29N01	74	(244)	3/59	612
-27N01	68	(222)	3/59	665	-33Q01	63	(205)	3/59	571
-27R01	224	(736)	3/59	665	-34A01	125	(410)	6/49	525
-33R01	53	(175)	3/65	6 460	-34A02	159	(520)	8/51	626
4N/7W-02D01	--	(--)	3/59	20 560	-34E02	85	(280)	4/63	534
-04F01	56	(184)	8/58	789	-34G01	70	(230)	8/54	943
5N/6W-30D01	47	(155)	3/59	855	-34G02	85	(280)	9/60	529

*All exceed recommended limit of Total Dissolved Solids = 500 mg/L.

Boron

Boron in drinking water is not generally considered a health hazard, because concentrations up to 30 mg/L are not considered harmful to humans. Although a minor constituent of most water, boron is extremely important in agriculture. An amount greater than 2 mg/L is toxic to most plants, but small amounts are essential to plant growth. Boron is toxic to many plants, such as citrus, grapes, apples, and walnuts, in concentrations of less than 1 mg/L. Boron concentrations below 0.5 mg/L are satisfactory for all crops (Ayers and Branson, 1975).

Of the 50 wells tested in the Petaluma Valley, 17 produce water with boron concentrations in excess of 0.5 mg/L, and 5 of these 17 wells produce water with boron in excess of 2 mg/L (Table 7 and Figure 14D).

High boron in the Petaluma Valley is generally the result of sea water intrusion (as in wells 3N/6W-3C1 and 4N/7W-2D1) or connate water trapped within fine-grained marine sediments of the Petaluma Formation (as in wells 4N/6W-27N1 and -27R1, 5N/7W-24F1 and -24B1).

In the Petaluma Valley, high concentrations of boron in ground water are always found in association with water having a moderate-to-severe sodium hazard and are frequently found in association with high salinity and TDS. The potential for movement of boron-rich ground water is the same as that for water containing high sodium, salinity, or TDS.

Nitrate

High concentrations of nitrate can cause methemoglobinemia, an oxygen deficiency in infants. For this reason, a recommended drinking water limit of 45 mg/L of nitrate (10 mg/L expressed as nitrogen) has been established by the California Administrative Code, Title 22 (California Department of Health, 1977).

Nitrates are produced by aerobic stabilization of organic nitrogen. The presence of nitrate in ground water is usually indicative of pollution from surface sources such as septic-tank leach-fields, fertilizers, or livestock and poultry farms.

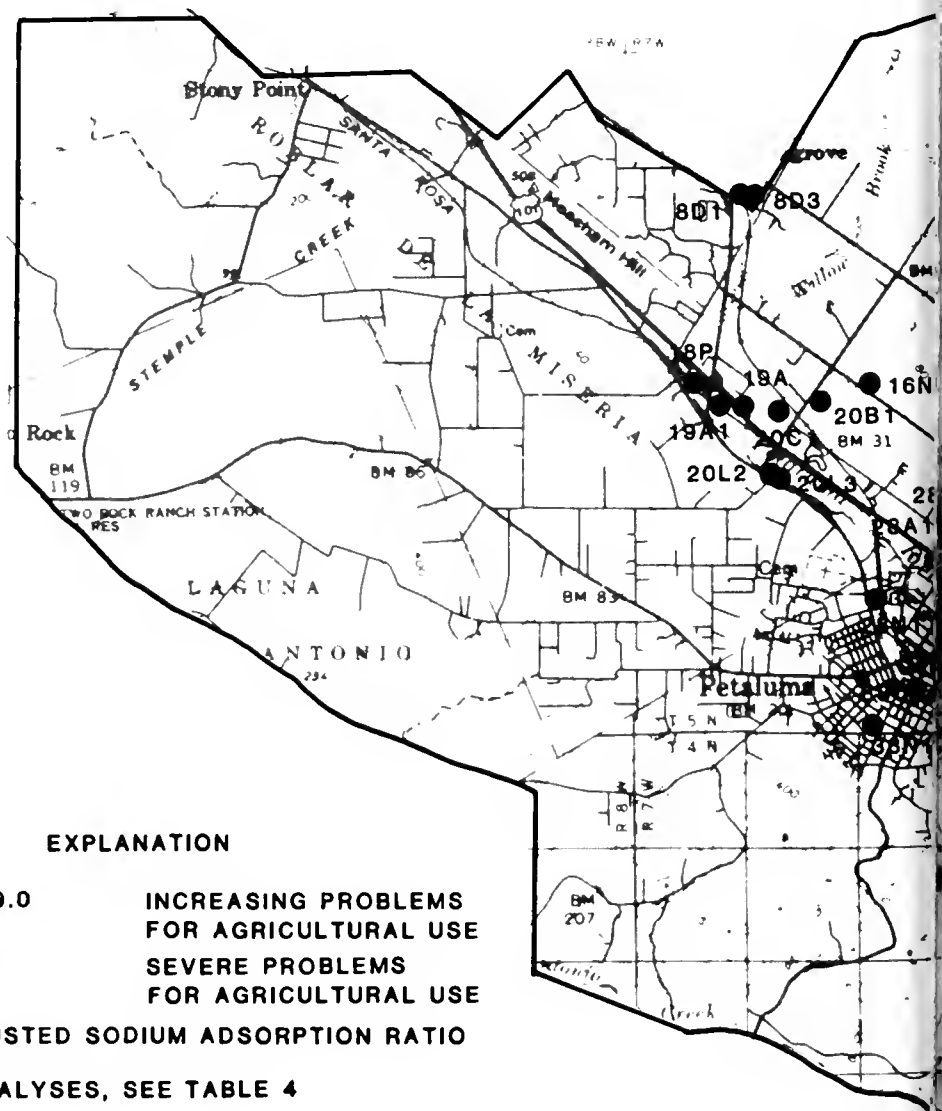
In the area northwest of Petaluma, the major source of nitrate contamination

Table 7
BORON IN GROUND WATER
IN EXCESS OF RECOMMENDED STANDARDS

Well Number:	Depth	Date	Boron
:metres:(feet):	:mo/yr	:mg/L *	
3N/5W-06C01	15 (50)	3/59	0.59
3N/6W-03C01	-- (--)	4/62	0.92
-11B01	76 (250)	3/58	0.56
4N/6W-07H01	11 (35)	4/60	2.3
-07H02	-- (--)	11/65	3.1
-08E01	23 (74)	8/79	2.4
-21Q01	141 (464)	11/65	1.2
-27N01	68 (222)	9/60	0.62
-27R01	224 (736)	8/58	0.96

Well Number:	Depth	Date	Boron
:metres:(feet):	:mo/yr	:mg/L *	
4N/7W-02D01	19 (62)	9/60	1.01
5N/6W-30D01	47 (155)	8/58	0.81
5N/7W-19A01	99 (325)	9/60	0.73
-24B01	198 (650)	9/49	6.96
-24F01	578 (1,896)	10/50	3.40
-34A02	-- (--)	8/51	1.08
-34G01	70 (230)	8/54	0.66
-35H01	165 (542)	7/49	0.6

*All exceed recommended limit of Boron = 0.5 mg/L.



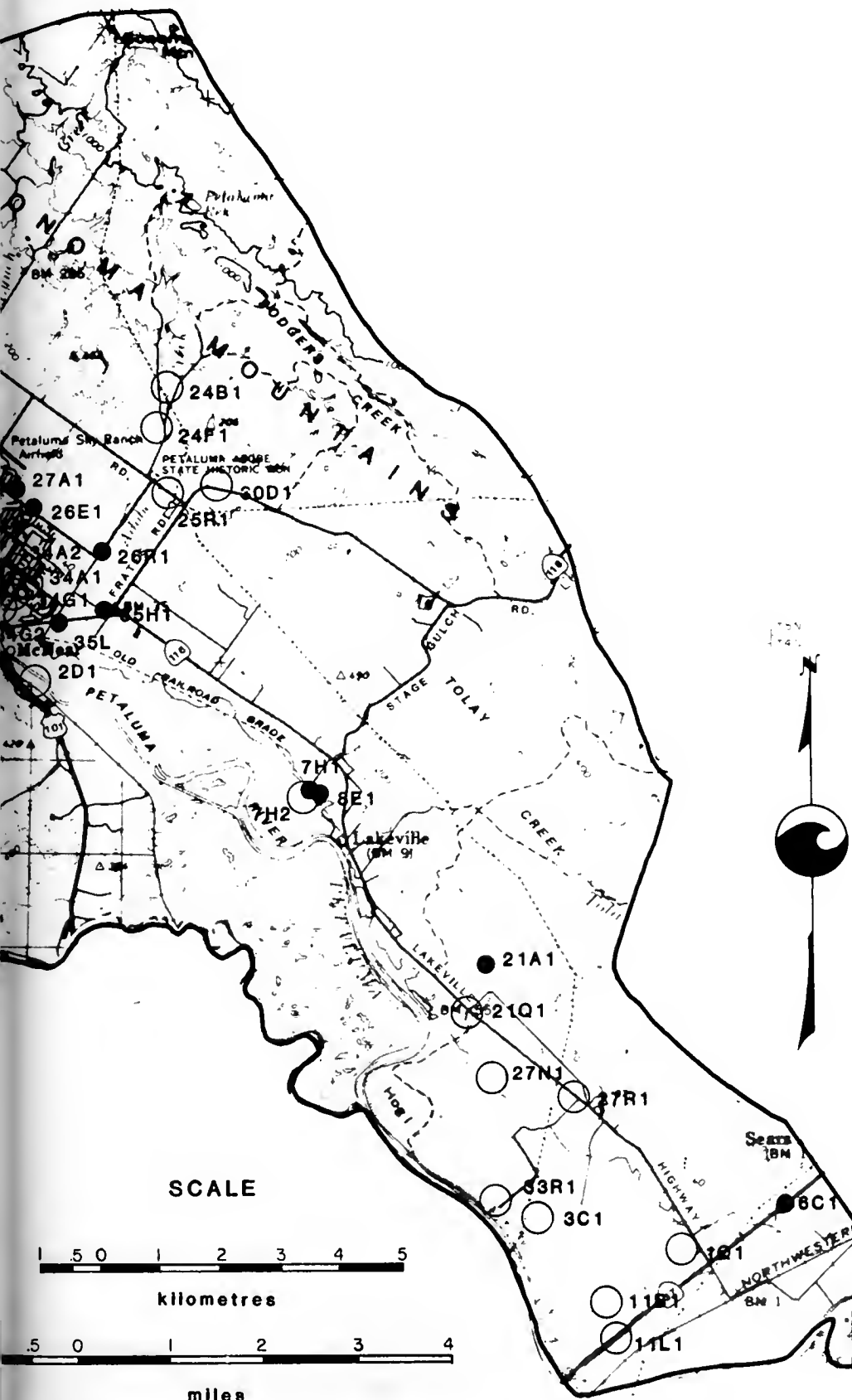
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CENTRAL DISTRICT

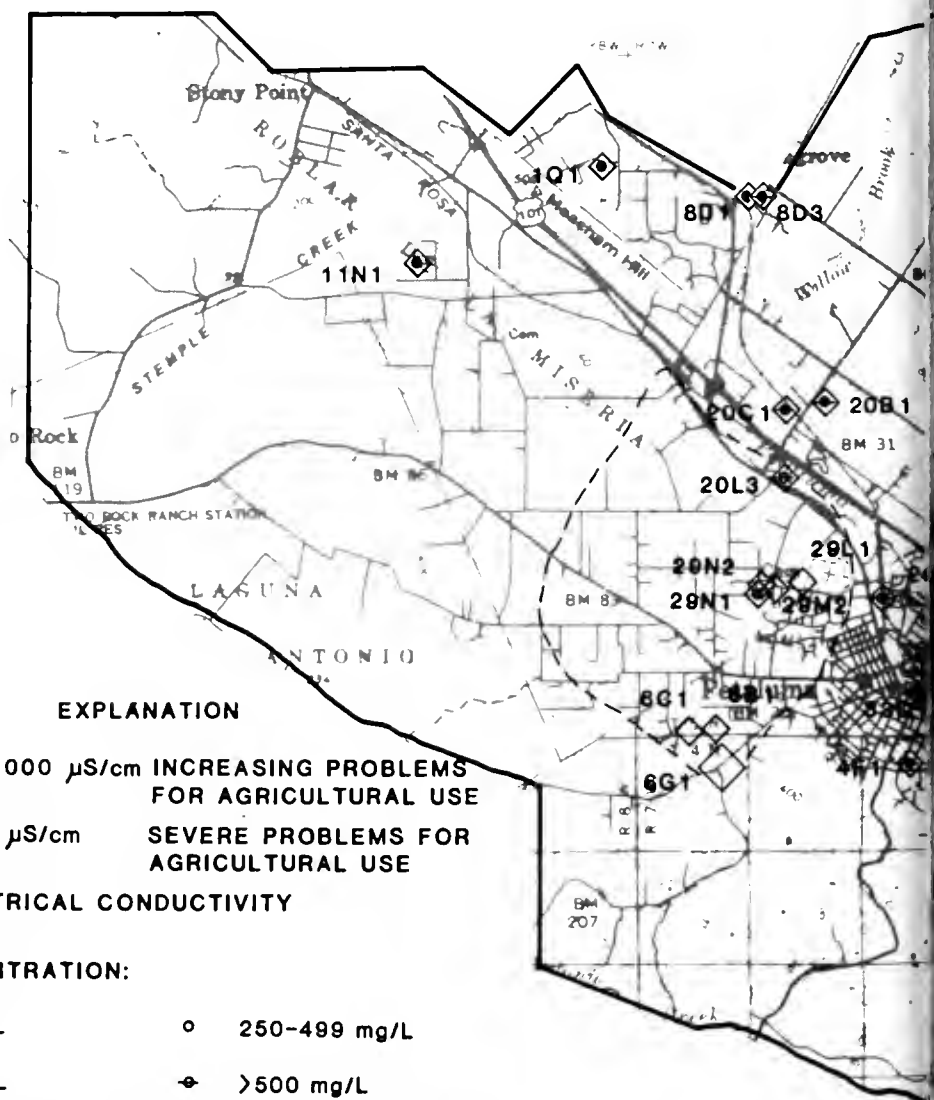
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SODIUM IN GROUND WATER
IN EXCESS OF RECOMMENDED STANDARDS

FIGURE 14A





EXPLANATION

- ◊ E.C. \approx 150-3000 μ S/cm INCREASING PROBLEMS FOR AGRICULTURAL USE
 - ◊ E.C. $>$ 3000 μ S/cm SEVERE PROBLEMS FOR AGRICULTURAL USE
- E.C. = ELECTRICAL CONDUCTIVITY

CHLORIDE CONCENTRATION:

- 106-141 mg/L
- ◊ 142-249 mg/L
- ◊ 250-499 mg/L
- ◊ $>$ 500 mg/L

E.C. IN AREA ENCLOSED IN DASHED LINE IS APPROXIMATELY 1000 μ S/cm
FOR DATES OF ANALYSES, SEE TABLE 5

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◊
SALINITY IN GROUND WATER
IN EXCESS OF RECOMENDED STANDARDS

SUGGESTED LIMITS OF CHLORIDE CONCENTRATION

AGRICULTURAL USE:

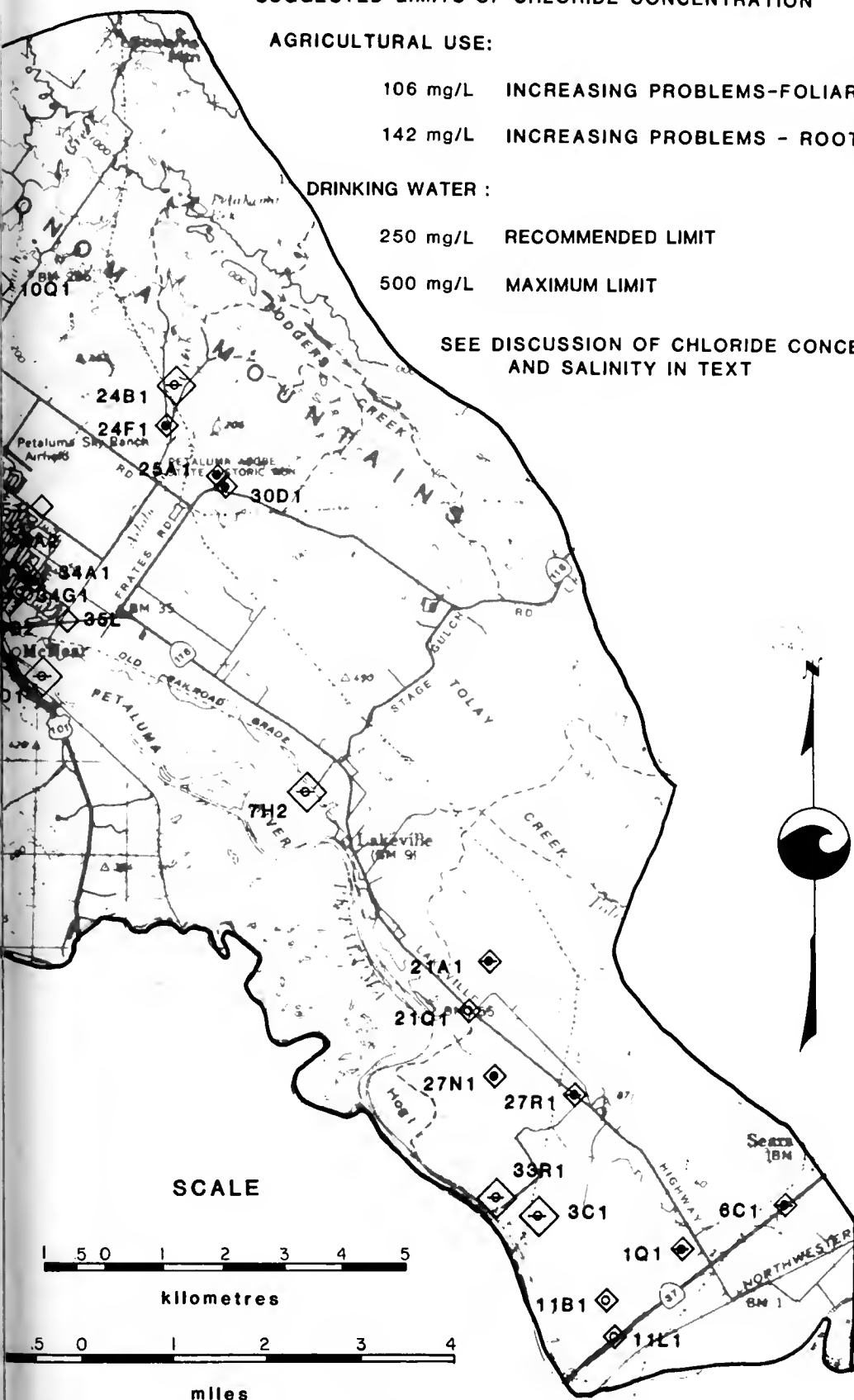
106 mg/L INCREASING PROBLEMS-FOLIAR ABSORPTION

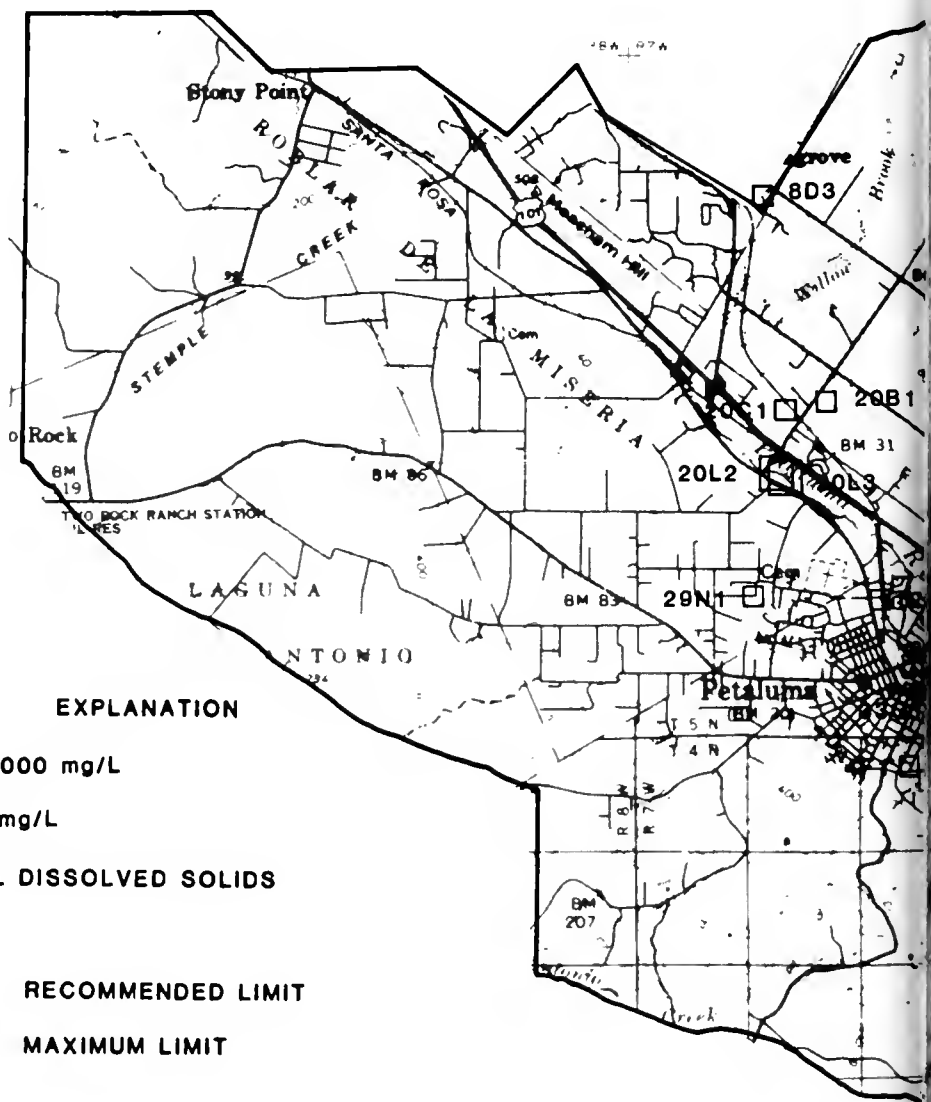
142 mg/L INCREASING PROBLEMS - ROOT ABSORPTION

DRINKING WATER :

250 mg/L RECOMMENDED LIMIT

500 mg/L MAXIMUM LIMIT

SEE DISCUSSION OF CHLORIDE CONCENTRATION
AND SALINITY IN TEXT



EXPLANATION

□ TDS = 500-1000 mg/L

■ TDS > 1000 mg/L

TDS = TOTAL DISSOLVED SOLIDS

DRINKING WATER:

500 mg/L RECOMMENDED LIMIT

1000 mg/L MAXIMUM LIMIT

FOR DATES OF ANALYSES, SEE TABLE 6

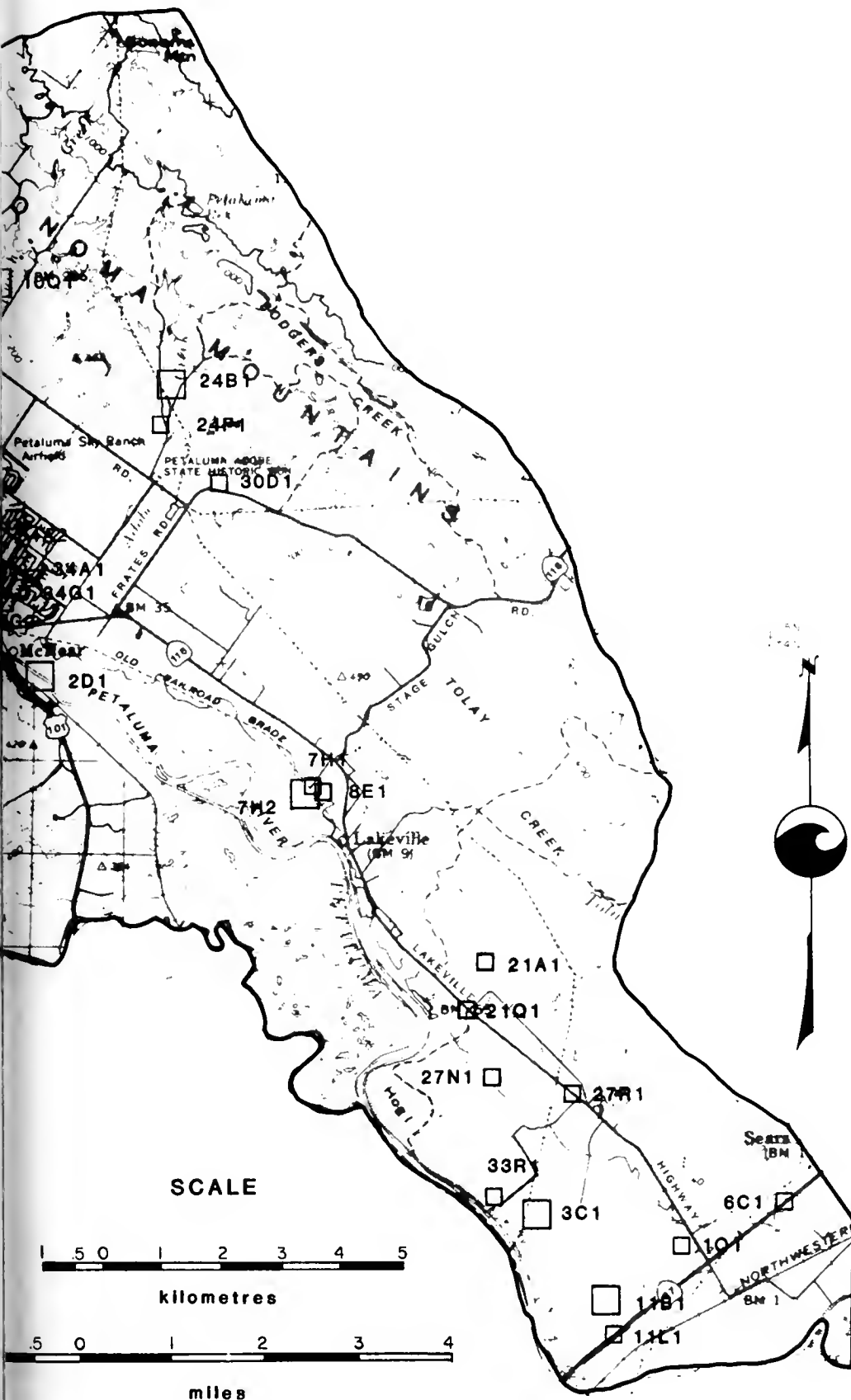
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CENTRAL DISTRICT

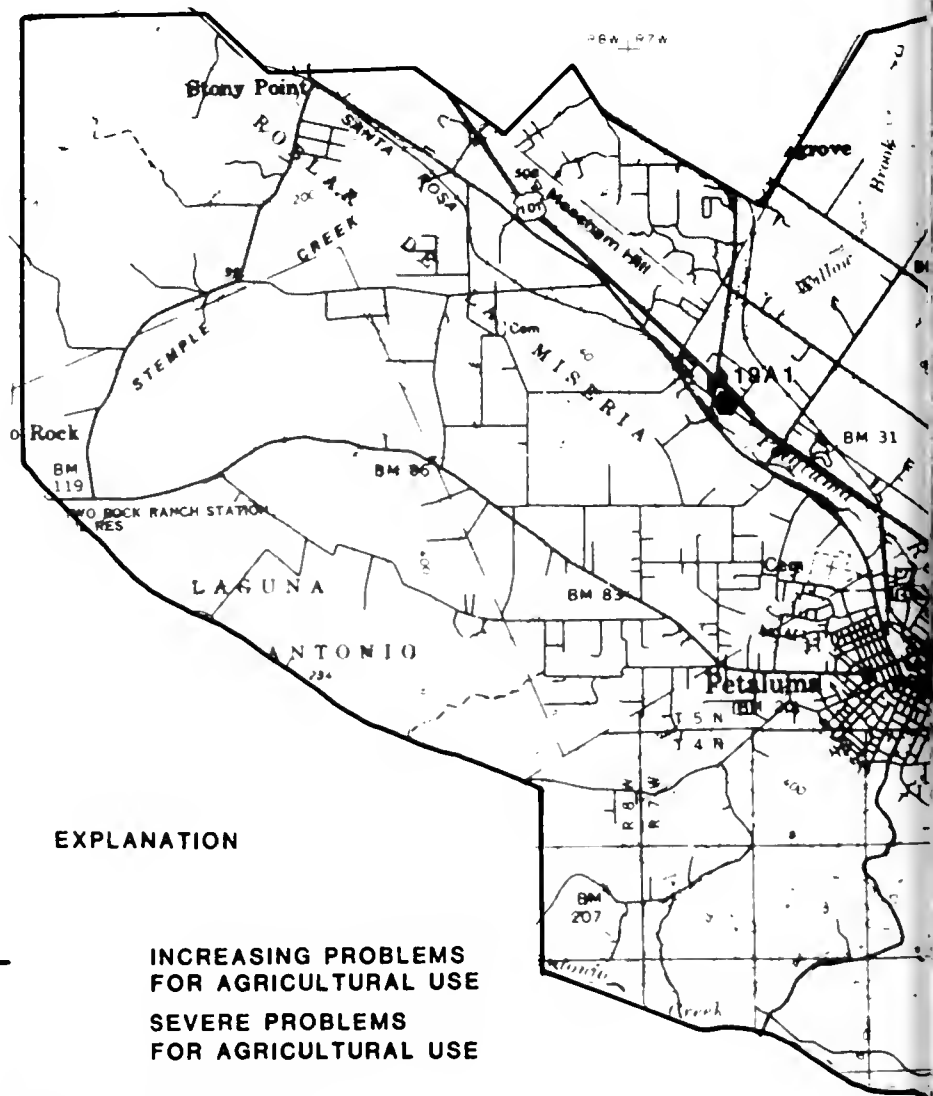
PETALUMA VALLEY SONOMA COUNTY GROUND WATER STUDY



**TOTAL DISSOLVED SOLIDS IN GROUND WATER
IN EXCESS OF RECOMMENDED STANDARDS**

FIGURE 14C





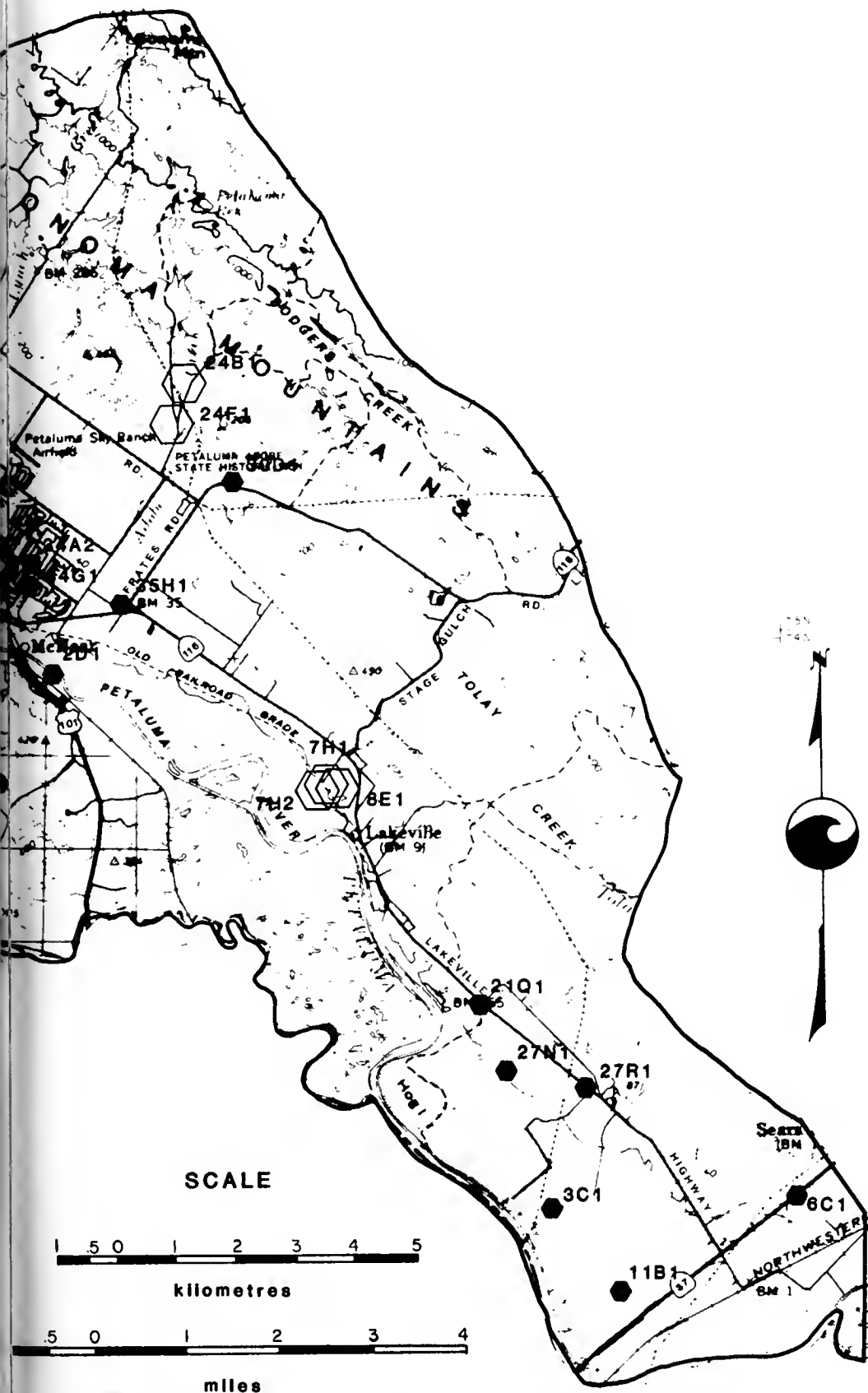
FOR DATES OF ANALYSES, SEE TABLE 7

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PETALUMA VALLEY
SONOMA COUNTY GROUND WATER STUDY



**BORON IN GROUND WATER
IN EXCESS OF RECOMMENDED STANDARDS**



appears to be livestock and poultry manure that was disposed of in unlined pits or on the land surface. Nitrates were leached from the manure piles by rainfall and infiltrated downward to the ground water body. A secondary source of nitrate contamination in some areas is septic-tank leach-field systems; fecal coliform bacteria in ground water samples indicates contamination from this source.

Once nitrate is present in the ground water, the contamination can spread vertically and horizontally, unless confining layers of clay or other poorly permeable materials are present. Gravel-packed wells provide a conduit for contaminated water to move vertically from a shallow zone to a deeper zone; the contaminated water moves through the perforations and gravel pack. For this reason abandoned wells should be properly filled and sealed, and deep sanitary seals that extend below the contaminated zone (about 15 m, or 50 ft, in the area northwest of Petaluma) should be installed in new wells. As a minimum requirement, seals should extend at least to the first impermeable stratum. A temporary ordinance now in effect for the area northwest of Petaluma requires seals 15 m (50 ft) deep or to the first impermeable stratum (County of Sonoma Ordinance 2607). A seal of 30 m (100 ft) would reduce the likelihood of well contamination by shallow, nitrate-rich ground water. (See Ritchie, 1981, Water Well Standards.)

Before 1979, water quality data collected in the Petaluma Valley at random locations indicated that 5 of the 54 wells sampled produced water containing nitrates in excess of recommended limits. During the winter of 1978-79, a case of methemoglobinemia was diagnosed in an infant whose family lived in the area northwest of Petaluma. Because of this incident, an extensive sampling program was conducted cooperatively in this area in 1979 by DWR, the California Department of Health Services, and the Sonoma County Health Department.

Of the 200 wells sampled in 1979, 33 percent produced water containing nitrate in

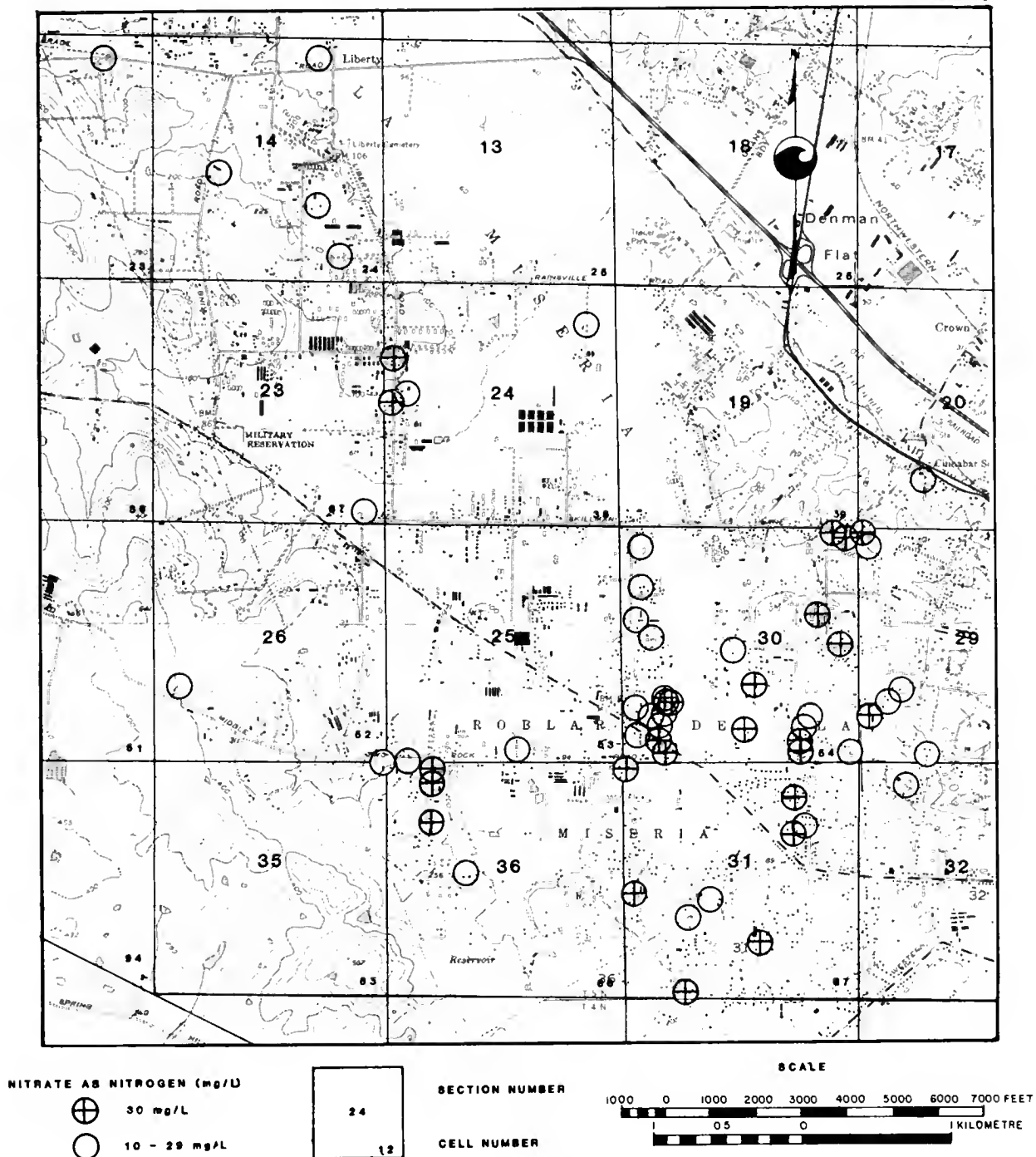
excess of the recommended limits (Figure 15 and Table 8). Because of this widespread contamination, DWR, Central District, is conducting a cooperative study with the previously listed agencies and the San Francisco Regional Water Quality Control Board to better define the vertical and horizontal extent of the contaminated water and determine the source of contamination. Information from this study will be published as a District Report in April 1982 (Perkins, in progress).

Preliminary data indicate that the zone of nitrate contamination extends from the land surface to perhaps 15 m (50 ft) deep. There are no vertical barriers within the Merced Formation in the western uplands except for isolated lava flows of the Sonoma Volcanics (Plate 1 and Figures 5A-E). The nonwater-yielding Tolay Volcanics and Franciscan complex rocks form horizontal barriers beneath the Merced Formation and vertical barriers where they are exposed at the surface adjacent to the Merced Formation. The concentration of nitrate in ground water may actually increase near these margins because the Tolay and Franciscan rocks restrict ground water migration.

Electrical conductivities appear to be higher than average in nitrate-contaminated water because leachate from animal wastes or septic tanks is generally high in salts. In the area west of Petaluma, two wells of similar construction 0.40 kilometre (0.25 mile) apart had nitrate concentrations above recommended limits and EC values of 500 uS/cm and 2 000 uS/cm (wells 5N/8W-36C41 and 5N/8W-36C4). The well with the higher nitrate and EC values is near holding ponds used for dairy wastes (DWR, unpublished data).

The extent and sources of nitrate contamination in other areas of the Petaluma Valley cannot be evaluated as to extent or source because of the limited data available. Further sampling should be conducted near wells known to be affected to define the size of the nitrate contamination problem in these areas.

FIGURE 15



STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
CENTRAL DISTRICT
PETALUMA VALLEY
SONOMA COUNTY GROUND WATER STUDY

**NITRATE IN EXCESS OF RECOMMENDED STANDARDS
IN THE AREA NORTHWEST OF THE CITY OF PETALUMA**

Table 8

NITRATE IN GROUND WATER
IN EXCESS OF RECOMMENDED STANDARDS

Well Number	Depth	Date	Nitrate		Well Number	Depth	Date	Nitrate	
			1/NO ₃ ⁻	2/				1/NO ₃ ⁻	2/
			mo/yr	mg/L:mg/L				mo/yr	mg/L:mg/L
3N/6W-03C01	--	(--)	9/61	45	5N/7W-30Q04	--	(--)	9/79	21
4N/7W-04F01	56	(184)	8/58	216	-30Q06	--	(--)	10/79	32
5N/7W-20L02	19	(62)	3/59	191	-30R02	--	(--)	9/79	20
-20L03	15	(50)	4/64	118	-30R04	--	(--)	9/79	25
-20N05	--	(--)	10/79	11	-30R07	--	(--)	10/79	20
-28N01	19	(62)	8/58	106	-31B06	--	(--)	9/79	31
-29D04	--	(--)	10/79	70	-31D01	--	(--)	10/79	39
-29D07	--	(--)	10/79	16	-31G01	--	(--)	9/79	25
-29M02	73	(238)	10/79	20	-31G02	--	(--)	9/79	11
-29N02	--	(--)	9/79	36	-31G03	--	(--)	10/79	15
-29N03	44	(144)	9/79	11	-31L01	59	(192)	10/79	24
-29N05	--	(--)	9/79	18	-31M01	--	(--)	10/79	31
-30A01	36	(118)	10/79	43	-31M03	--	(--)	10/79	10
-30A03	--	(--)	10/79	31	-31P01	--	(--)	10/79	33
-30D02	--	(--)	10/79	59	-31Q01	--	(--)	10/79	56
-30E02	57	(188)	10/79	27	-32D01	--	(--)	9/79	28
-30E03	--	(--)	10/79	31	5N/8W-11R01	91	(300)	10/79	17
-30E04	--	(--)	10/79	29	-14K01	--	(--)	10/79	11
-30H03	--	(--)	9/79	67	-14L01	61	(200)	10/79	15
-30H04	--	(--)	10/79	40	-14R01	34	(110)	10/79	24
-30K09	--	(--)	10/79	66	-15A01	--	(--)	10/79	17
-30L04	--	(--)	10/79	12	-23R01	--	(--)	10/79	22
-30M01	--	(--)	9/79	53	-24A01	--	(--)	10/79	16
-30M02	--	(--)	9/79	52	-24E01	--	(--)	10/79	21
-30N03	--	(--)	9/79	33	-24E02	61	(200)	10/79	38
-30N04	--	(--)	9/79	22	-24M04	--	(--)	10/79	38
-30N05	--	(--)	9/79	27	-25Q01	--	(--)	10/79	19
-30N06	--	(--)	9/79	14	-26M01	--	(--)	10/79	11
-30N07	--	(--)	9/79	27	-35A01	--	(--)	10/79	12
-30N08	--	(--)	9/79	24	-36C03	--	(--)	10/79	83
-30N09	--	(--)	9/79	17	-36C04	82	(269)	10/79	17
-30N10	--	(--)	9/79	22	-36D01	61	(200)	10/79	35
-30N11	--	(--)	10/79	38	-36E02	--	(--)	10/79	69
-30Q03	--	(--)	9/79	34	-36F01	13	(42)	10/79	15

1/ All exceed recommended limit of nitrate of 45 mg/L for infants.

2/ All exceed recommended limit of nitrate as nitrogen of 10 mg/L for infants.

Hardness

Ground water containing calcium and magnesium salts is divided into two general classifications: carbonate hardness and noncarbonate hardness. Carbonate hardness becomes apparent after water has been heated, causing the soluble calcium and magnesium bicarbonates to precipitate as insoluble carbonates. The precipitates adhere to heated surfaces, such as the inside of water heaters and hot water pipes, and ultimately reduce the capacity of the fixture. Noncarbonate hardness is not affected by heat because it is

principally caused by the presence of calcium sulfate; since few analyses of noncarbonate hardness in the study area are available, it will not be discussed here. Both forms of hardness reduce the cleansing ability of many soaps and detergents.

The hardness of ground water is variable. Soft waters are those with a hardness of less than 60 mg/L of calcium carbonate; moderately hard waters are those with a hardness range of from 61 to 200 mg/L. Hard waters are those that have a hardness in excess of 200 mg/L.

Available data indicate that most ground water in the Petaluma Valley varies from moderately hard to hard. The hardest water is generally found in areas affected by sea water intrusion or underlain by poor quality connate water bodies.

The greatest potential for a change in hardness is near areas affected by sea water intrusion. If ground water pumping produces a landward gradient, encouraging inland movement of sea water, hardness will increase as sea water moves into alluvial fan deposits.

Iron and Manganese

The presence of excessive iron and manganese in ground water is a common problem. Both of these constituents can impart a metallic taste to water or to food prepared with such water. The metallic impurities may also stain fixtures, fabrics, and utensils. The iron and manganese deposits build up in pressure tanks, water heaters, and pipes and reduce the available quantity and pressure of the water supply. The recommended limit is

0.3 mg/L for iron and 0.05 mg/L for manganese.

To obtain an accurate analysis of the amount of iron and manganese in a water sample, the sample must be acidified with nitric acid immediately after collection to stabilize the metallic constituents. If this is not done, some iron and manganese will precipitate out of solution. If plastic jugs are used for sampling, some iron and manganese will adhere to the plastic. Acidification of water samples has rarely been performed in the Petaluma Valley; therefore, a general statement on the occurrence and movement of iron- and manganese-rich water cannot be made.

Water containing excessive iron and manganese has been produced from wells:

- ° Tapping alluvial fan deposits.
- ° Tapping the Petaluma Formation.
- ° Tapping the Sonoma Volcanics.

Table 9 lists wells in the Petaluma Valley known to produce water with iron or manganese in excess of recommended limits.

Table 9

IRON AND MANGANESE IN GROUND WATER IN EXCESS OF RECOMMENDED STANDARDS

Well Number	Depth :metres:(feet)	Date : mo/yr	Iron		Man- ganese
			Total*	Dis- solved	
			mg/L	mg/L	mg/L
3N/6W-01Q01	69 (223)	4/60	0.93**		---
-03C01	-- (--)	3/59	4.60**		---
-11B01	76 (250)	3/58	0.57**		---
4N/6W-07H01	11 (35)	4/60	0.33**		---
-07H02	-- (--)	4/60	0.31**		---
-21A01	80 (259)	8/74	0.31**		0.02
-21Q01	141 (464)	4/60	1.20**		---
-27N01	68 (222)	4/60	5.60**		---
-33R01	53 (175)	4/60	6.00**		---
4N/7W-02D01	19 (62)	4/60	6.50**		---
5N/7W-08D01	-- (--)	5/47	0.03		0.07**
-08D03	42 (138)	3/59	1.2**		---
-19A01	99 (325)	4/60		1.1**	---
-19A	182 (596)	9/77	0.22		0.07**
-19N01	55 (180)	3/59	0.59**		---
-20B01	183 (600)	5/47	0.03		0.09**
5N/7W-22Q01	28 (92)	7/49	0.19		0.30**
-22Q02	30 (97)	8/49	0.13		0.10**
-22Q	110 (360)	5/77	0.18		0.19**
-25C01	72 (235)	5/47	0.26		0.15**
-26E01	184 (605)	3/59	1.20**		---
-26R01	131 (428)	2/49	0.03		0.07**
-27A01	130 (425)	3/59	0.59**		---
-28A02	30 (99)	5/49	0.14		0.11**
-28A03	85 (280)	5/49	0.01		0.14**
-28H03	28 (92)	4/60		0.61**	0.14**
-28H04	25 (83)	5/49	0.01		0.06**
-28H05	143 (468)	5/49	0.03		0.06**
-28N01	19 (62)	4/61		0.01	0.08**
-34E02	85 (280)	4/60	0.52**		---
-35J	85 (280)	7/77	0.30**		<0.05
-35K01	24 (78)	4/60	0.44**		---
-35L	70 (229)	5/77	0.06		0.10**

* Value for iron given as "Total" or no distinction made as to type of analysis.

**Concentration is above recommended limits of 0.3 mg/L iron or 0.05 mg/L manganese.

Sources of iron and manganese are varied. Iron is frequently present in the cementing material of sandstones and within shales. Iron is also found in the soils produced by weathering of these rocks. Iron may be added to ground water from contact with well casing, pump parts, piping, storage tanks, and other iron objects. It can be derived from iron bacteria that grow in some well casings.

Manganese found in ground water is most frequently the result of solution of manganese from soils and sediments aided by anaerobic bacteria under reducing conditions.

In some parts of California, water rich in iron and manganese occurs near the bottom of various individual aquifers. Because iron and manganese ions are relatively heavy, they tend to settle in an aquifer until they are concentrated just above a clay bed. Water drawn from a well perforated near the bottom of an aquifer would therefore tend to have a greater concentration of iron and manganese. In the Petaluma Valley, however, data are insufficient to evaluate this phenomenon.

Well Owner Questionnaire Results

To determine well owners' opinions of their ground water quality, the Sonoma County Water Agency mailed questionnaires in 1977 to all rural property owners in Sonoma County who do not receive water from municipal water systems. The questionnaires requested information on ground water taste, odor, and color. The responses were grouped according to

assessor's parcel books (Figure 16). Within each parcel book area, responses were separated according to well depth:

- ° Shallow wells, 0-46 m (0-150 ft) deep.
- ° Intermediate wells, 46-107 m (151-350-ft) deep.
- ° Deep wells, greater than 107 m (350 ft) deep.

Within each depth range, the number of wells with each of the following problems was tabulated:

- ° Taste
- ° Odor
- ° Color
- ° Other (problem)
- ° None (no problem)

Since a single well could have more than one problem, two other tabulations were added: (1) taste, odor, or color; and (2) taste, odor, color, or other. The responses to the questionnaires are tabulated in Table 10.

The most common complaints about water from shallow wells were taste and color. No complaint was more common than others about water from intermediate-depth wells. Few complaints were reported about water from deep wells.

Some common causes of unpleasant taste are excessive hardness, salinity, sodium, iron and manganese, and sulfides. Some causes of colored water are excessive iron and manganese and the pumping of sand. Unpleasant odor can be caused by excessive iron and manganese or hydrogen sulfide.

FIGURE 16

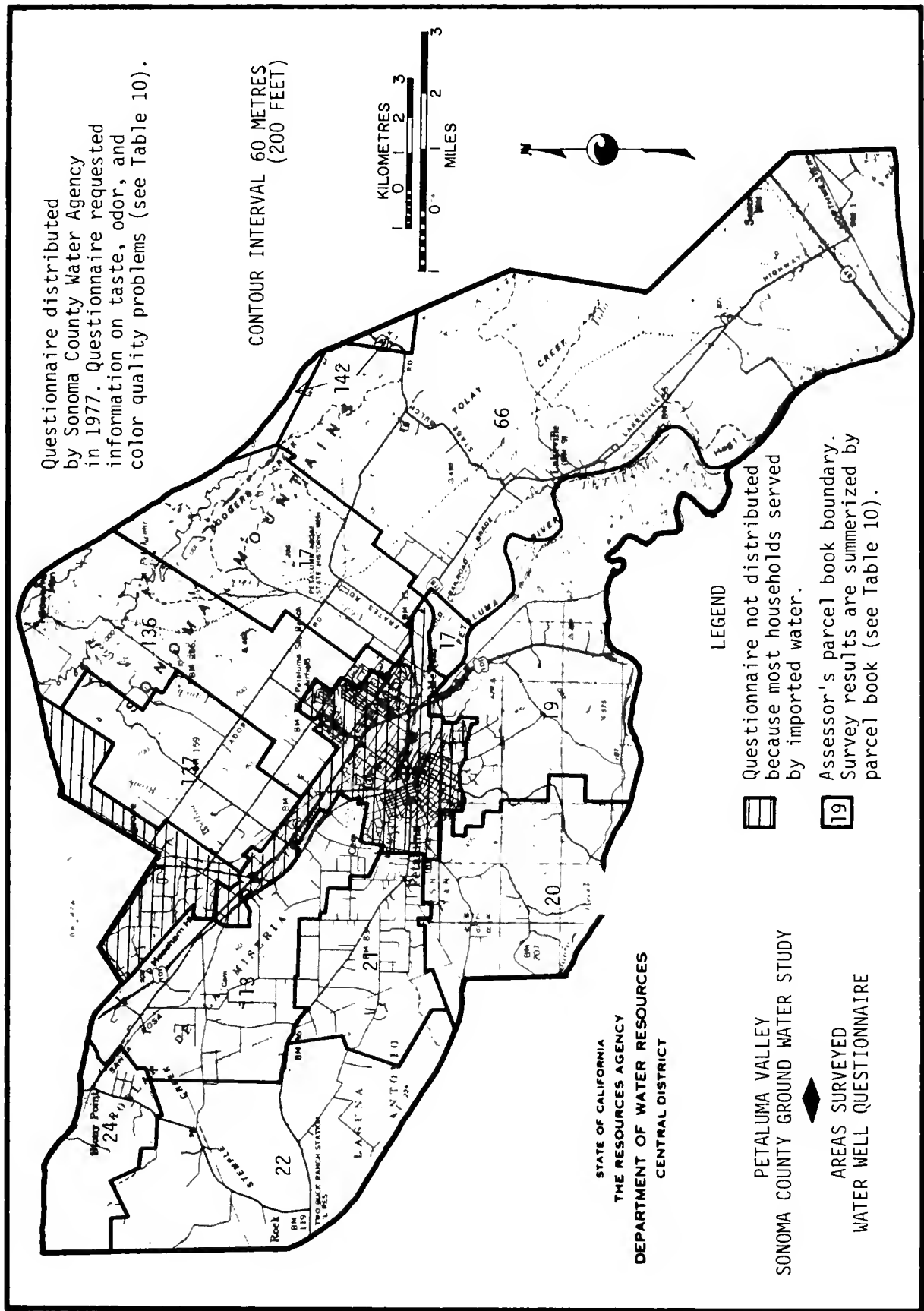


TABLE 10

WATER WELL QUESTIONNAIRE RESPONSES

1977 DATA

1/

ASSESSORS PARCEL BOOK NO. 17	NUMBER OF RESPONSES WITH INDICATED QUALITY PROBLEM				SUMMARY
QUALITY PROBLEM	SHALLOW WELLS 0-150 FT	INTERMEDIATE WELLS 151-350 FT	DEEP WELLS > 350 FT	WELLS WITH DEPTH UNKNOWN	ALL WELLS
TASTE	0	0	0	0	0
ODOR	3	0	0	0	3
COLOR	3	0	0	2	5
OTHER	0	0	0	0	0
NONE	5	0	0	2	7
TASTE, ODOR OR COLOR	3	0	0	2	5
TASTE, ODOR, COLOR OR OTHER	3	0	0	2	5
NUMBER OF WELLS IN SURVEY	8	0	0	4	12
% WELLS WITH T.O.C QUALITY PROBLEM	37.5%	N/A	N/A	50.0%	41.7%
% WELLS WITH T.O.C.X QUALITY PROBLEM	37.5%	N/A	N/A	50.0%	41.7%
ASSESSORS PARCEL BOOK NO. 19	NUMBER OF RESPONSES WITH INDICATED QUALITY PROBLEM				SUMMARY
QUALITY PROBLEM	SHALLOW WELLS 0-150 FT	INTERMEDIATE WELLS 151-350 FT	DEEP WELLS > 350 FT	WELLS WITH DEPTH UNKNOWN	ALL WELLS
TASTE	5	0	0	3	8
ODOR	2	0	0	0	2
COLOR	0	0	1	3	4
OTHER	3	0	0	2	5
NONE	19	0	0	4	23
TASTE, ODOR OR COLOR	6	0	1	3	10
TASTE, ODOR, COLOR OR OTHER	7	0	1	5	13
NUMBER OF WELLS IN SURVEY	26	0	1	9	36
% WELLS WITH T.O.C QUALITY PROBLEM	23.1%	N/A	100.0%	33.3%	27.8%
% WELLS WITH T.O.C.X QUALITY PROBLEM	26.9%	N/A	100.0%	55.6%	36.1%
ASSESSORS PARCEL BOOK NO. 20	NUMBER OF RESPONSES WITH INDICATED QUALITY PROBLEM				SUMMARY
QUALITY PROBLEM	SHALLOW WELLS 0-150 FT	INTERMEDIATE WELLS 151-350 FT	DEEP WELLS > 350 FT	WELLS WITH DEPTH UNKNOWN	ALL WELLS
TASTE	0	2	0	1	3
ODOR	0	2	0	1	3
COLOR	3	2	0	1	6
OTHER	2	3	0	1	6
NONE	30	5	0	3	41
TASTE, ODOR OR COLOR	3	2	0	1	6
TASTE, ODOR, COLOR OR OTHER	5	4	0	1	10
NUMBER OF WELLS IN SURVEY	35	12	0	4	51
% WELLS WITH T.O.C QUALITY PROBLEM	8.6%	16.7%	N/A	25.0%	11.8%
% WELLS WITH T.O.C.X QUALITY PROBLEM	14.3%	33.3%	N/A	25.0%	19.6%
ASSESSORS PARCEL BOOK NO. 21	NUMBER OF RESPONSES WITH INDICATED QUALITY PROBLEM				SUMMARY
QUALITY PROBLEM	SHALLOW WELLS 0-150 FT	INTERMEDIATE WELLS 151-350 FT	DEEP WELLS > 350 FT	WELLS WITH DEPTH UNKNOWN	ALL WELLS
TASTE	10	6	0	5	21
ODOR	5	0	0	3	14
COLOR	12	10	0	9	31
OTHER	16	13	0	1	30
NONE	64	26	3	30	123
TASTE, ODOR OR COLOR	20	15	0	11	46
TASTE, ODOR, COLOR OR OTHER	32	25	0	12	69
NUMBER OF WELLS IN SURVEY	114	63	3	42	224
% WELLS WITH T.O.C QUALITY PROBLEM	17.2%	23.8%	0%	26.2%	20.5%
% WELLS WITH T.O.C.X QUALITY PROBLEM	27.6%	39.7%	0%	26.6%	30.8%
ASSESSORS PARCEL BOOK NO. 22	NUMBER OF RESPONSES WITH INDICATED QUALITY PROBLEM				SUMMARY
QUALITY PROBLEM	SHALLOW WELLS 0-150 FT	INTERMEDIATE WELLS 151-350 FT	DEEP WELLS > 350 FT	WELLS WITH DEPTH UNKNOWN	ALL WELLS
TASTE	12	1	0	0	13
ODOR	0	1	0	0	1
COLOR	8	0	0	0	8
OTHER	1	1	0	0	2
NONE	29	10	0	9	48
TASTE, ODOR OR COLOR	14	2	0	0	16
TASTE, ODOR, COLOR OR OTHER	15	3	0	0	18
NUMBER OF WELLS IN SURVEY	44	13	0	9	66
% WELLS WITH T.O.C QUALITY PROBLEM	31.8%	15.4%	N/A	0%	24.2%
% WELLS WITH T.O.C.X QUALITY PROBLEM	34.1%	23.1%	N/A	0%	27.3%
ASSESSORS PARCEL BOOK NO. 24	NUMBER OF RESPONSES WITH INDICATED QUALITY PROBLEM				SUMMARY
QUALITY PROBLEM	SHALLOW WELLS 0-150 FT	INTERMEDIATE WELLS 151-350 FT	DEEP WELLS > 350 FT	WELLS WITH DEPTH UNKNOWN	ALL WELLS
TASTE	3	3	1	4	11
ODOR	2	3	0	6	11
COLOR	1	4	0	6	11
OTHER	0	4	0	1	5
NONE	12	7	0	4	23
TASTE, ODOR OR COLOR	3	6	1	6	16
TASTE, ODOR, COLOR OR OTHER	3	10	1	7	21
NUMBER OF WELLS IN SURVEY	15	17	1	11	44
% WELLS WITH T.O.C QUALITY PROBLEM	20.0%	35.3%	100.0%	54.5%	36.4%
% WELLS WITH T.O.C.X QUALITY PROBLEM	20.0%	58.8%	100.0%	63.6%	47.7%

FOR LOCATION OF ASSESSOR'S PARCEL BOOKS SEE FIGURE 16.

TABLE 10(continued)

ASSESSORS PARCEL BOOK NO. 6A QUALITY PROBLEM	SHALLOW WELLS 0-150 FT	NUMBER OF RESPONSES WITH INDICATED QUALITY PROBLEM INTERMEDIATE WELLS 151-350 FT	DEEP WELLS > 350 FT	WELLS WITH DEPTH UNKNOWN	SUMMARY ALL WELLS
TASTE	21	4	2	5	34
ODOR	15	2	0	7	24
COLOR	24	2	0	4	30
OTHER	15	4	0	5	27
NONE	82	7	1	20	110
TASTE, ODOR OR COLOR	32	5	2	10	47
TASTE, ODOR, COLOR OR OTHER	42	6	2	15	65
NUMBER OF WELLS IN SURVEY	124	13	3	35	175
% WELLS WITH T.O.C QUALITY PROBLEM	25.8%	23.1%	66.7%	28.6%	26.9%
% WELLS WITH T.O.C.X QUALITY PROBLEM	33.9%	46.2%	66.7%	42.9%	37.1%
ASSESSORS PARCEL BOOK NO. 113 QUALITY PROBLEM	SHALLOW WELLS 0-150 FT	NUMBER OF RESPONSES WITH INDICATED QUALITY PROBLEM INTERMEDIATE WELLS 151-350 FT	DEEP WELLS > 350 FT	WELLS WITH DEPTH UNKNOWN	SUMMARY ALL WELLS
TASTE	7	11	0	3	21
ODOR	7	10	0	3	20
COLOR	12	26	1	8	47
OTHER	8	15	0	4	27
NONE	35	46	2	15	98
TASTE, ODOR OR COLOR	14	31	1	9	55
TASTE, ODOR, COLOR OR OTHER	22	42	1	12	77
NUMBER OF WELLS IN SURVEY	57	66	3	27	175
% WELLS WITH T.O.C QUALITY PROBLEM	24.6%	35.2%	33.3%	33.3%	31.4%
% WELLS WITH T.O.C.X QUALITY PROBLEM	38.6%	47.7%	33.3%	44.4%	44.0%
ASSESSORS PARCEL BOOK NO. 136 QUALITY PROBLEM	SHALLOW WELLS 0-150 FT	NUMBER OF RESPONSES WITH INDICATED QUALITY PROBLEM INTERMEDIATE WELLS 151-350 FT	DEEP WELLS > 350 FT	WELLS WITH DEPTH UNKNOWN	SUMMARY ALL WELLS
TASTE	2	2	0	0	4
ODOR	3	1	0	0	4
COLOR	3	1	0	0	4
OTHER	4	5	0	0	9
NONE	10	7	2	3	22
TASTE, ODOR OR COLOR	2	4	0	0	6
TASTE, ODOR, COLOR OR OTHER	6	4	0	0	10
NUMBER OF WELLS IN SURVEY	16	14	2	3	35
% WELLS WITH T.O.C QUALITY PROBLEM	18.8%	18.2%	0%	0%	15.6%
% WELLS WITH T.O.C.X QUALITY PROBLEM	37.5%	36.4%	0%	0%	31.3%
ASSESSORS PARCEL BOOK NO. 137 QUALITY PROBLEM	SHALLOW WELLS 0-150 FT	NUMBER OF RESPONSES WITH INDICATED QUALITY PROBLEM INTERMEDIATE WELLS 151-350 FT	DEEP WELLS > 350 FT	WELLS WITH DEPTH UNKNOWN	SUMMARY ALL WELLS
TASTE	1	2	2	2	7
ODOR	2	1	2	1	6
COLOR	5	5	3	4	17
OTHER	2	2	2	1	7
NONE	11	9	2	4	26
TASTE, ODOR OR COLOR	4	7	3	3	17
TASTE, ODOR, COLOR OR OTHER	6	6	4	3	19
NUMBER OF WELLS IN SURVEY	19	17	5	7	48
% WELLS WITH T.O.C QUALITY PROBLEM	31.6%	41.2%	50.0%	42.9%	33.0%
% WELLS WITH T.O.C.X QUALITY PROBLEM	42.1%	47.1%	66.7%	42.9%	46.9%
ASSESSORS PARCEL BOOK NO. 142 QUALITY PROBLEM	SHALLOW WELLS 0-150 FT	NUMBER OF RESPONSES WITH INDICATED QUALITY PROBLEM INTERMEDIATE WELLS 151-350 FT	DEEP WELLS > 350 FT	WELLS WITH DEPTH UNKNOWN	SUMMARY ALL WELLS
TASTE	4	2	0	0	6
ODOR	2	0	0	0	2
COLOR	4	2	0	0	6
OTHER	3	2	0	2	7
NONE	34	11	0	10	55
TASTE, ODOR OR COLOR	6	5	0	0	11
TASTE, ODOR, COLOR OR OTHER	6	5	0	2	13
NUMBER OF WELLS IN SURVEY	43	16	0	12	71
% WELLS WITH T.O.C QUALITY PROBLEM	16.0%	18.8%	0%	0%	12.7%
% WELLS WITH T.O.C.X QUALITY PROBLEM	20.9%	31.3%	0%	16.7%	22.5%

CHAPTER 7. PLANNING FOR GROUND WATER MANAGEMENT

This chapter discusses alternative plans for ground water management in the Petaluma Valley. The concept of ground water basin management includes planned use of the ground water basin yield, storage space, transmission capability, and water in storage. It includes (1) protection of natural recharge and use of artificial recharge; (2) planned variation in amount and location of pumping over time; (3) use of ground water storage conjunctively with surface water from local and imported sources; and (4) protection and planned maintenance of ground water quality (Peters, 1980).

Use of ground water storage conjunctively with surface water is practiced in some areas in California where extensive use of ground water has partially dewatered a basin, creating additional space to store water underground. The Santa Clara Basin in Northern California, for example, is operated much like a bank account. During wet periods, excess surface water is "deposited" -- artificially recharged to fill the additional underground storage space. During dry periods, when there is less surface water, ground water is "withdrawn" -- pumped to supplement available surface water supplies.

Natural topographic constraints prevent the Petaluma Valley ground water basin from filling more than the present 84 percent indicated by the computer program TRANSCAP (Chapter 4). If the basins are more than the 84 percent full indicated by TRANSCAP, the additional ground water begins to "leak out" along roadcuts and into streams. This spillage of excess water that cannot be stored underground is a form of rejected recharge. The Petaluma Valley basin is therefore, in effect, completely filled at the present time. For a program similar to that

in the Santa Clara Basin to be practical, the volume of ground water in storage would have to be reduced below the present 84 percent to create storage space for water presently being rejected by the basin.

A ground water management program must be carefully examined from an economic viewpoint to determine costs versus the benefits of increased recharge. Lowered ground water tables require increased pumping lifts and, consequently, increased energy costs. Lowered water tables may also necessitate deepening of shallow wells and may result in costly litigation by owners of existing shallow wells against owners of new and high-use wells.

More ground water could be stored in some areas in the Petaluma Valley if ground water levels were drawn down further, making more storage space available. During the 1976-1977 drought, ground water levels dropped an average of 3 m (10 ft) below the normal fall lows, yet they returned to normal spring high after one winter of slightly higher than normal precipitation. The maximum that the basin could be drawn down and still recover in one winter is not known.

Certain special conditions control operation of the Petaluma Valley ground water basin. These special characteristics are:

- ° Generally poor quality ground water in the Petaluma Valley south of Petaluma.
- ° Potential for renewed sea water intrusion along the Petaluma River.
- ° Nitrate contamination in the upland areas northwest of the City of Petaluma.

Data collected by the U. S. Geological Survey (Cardwell, 1958) and DWR indicate that shallow ground water in the Petaluma Valley south of the City of Petaluma is contained in bay mud deposits and is generally brackish. Beneath these muds, ground water is generally connate water contained in the Petaluma Formation and is also of poor quality. The potential for increased use of ground water in this area is low. Good quality water is produced from alluvial fan deposits at the base of the hills that border the valley, but the quantity of water is limited.

In the valley area near Petaluma, wells are presently extracting water from alluvial fan deposits for municipal and agricultural uses. Increased use of ground water in this area is limited by the potential of sea water intrusion from the Petaluma River into aquifers in the fan deposits. In the late 1950s and early 1960s, the Petaluma municipal wells, which then provided all water for the city, had increasing problems from sea water intrusion as a result of the volume of municipal pumpage, which had created a landward gradient and drawn sea water into the freshwater aquifers. When ground water pumpage decreased as a result of surface water deliveries from the Russian River (beginning in 1962), the intrusion front stabilized and locally even moved back toward the Petaluma River. This action was a result of fresh water entering the alluvial fan aquifers from the east and moving toward the river, carrying with it some of the brackish sea water.

At present, the Petaluma municipal wells are collectively pumping about half the volume pumped in 1961, the year of heaviest pumping. The risk of renewed sea water intrusion increases as pumpage increases, and a return to historical high levels of pumpage (1 192 dam³ or 967 ac-ft in 1961) would probably renew intrusion.

Increased pumpage beyond historical high levels might create a contamination problem that would require a much longer period of reduced pumpage to eliminate. In some coastal aquifers where this type of contamination has occurred, it has resulted in the construction of expensive injection wells to pump fresh or nearly fresh water into the affected aquifer in an attempt to force the sea water front away from the ground water pumping areas.

In the upland area northwest of Petaluma large amounts of ground water are stored in the sandy Merced Formation. Many small domestic wells pump water for the use of individual households. Because of the large amounts of animal wastes dumped on the permeable soils in this area, the shallow ground water in this area is seriously contaminated with nitrate. Presently, the upper 15 m (50 ft) of the aquifer is generally affected. In some areas that have many septic-tank leach-field systems, the ground water is also polluted with fecal coliform derived from human wastes. Given the hydrologic conditions of the area, the polluted water will continue to spread.

Further use of the ground water resource in this upland area is possible as long as wells are deep and sufficiently sealed to prevent the near-surface contamination from entering the wells. Several households could draw water from a single very deep well, because the deeper ground water has not been contaminated. Deeper ground water does have certain aesthetic problems, such as taste, that are unrelated to the nitrate problem. To slow the rate of increase of nitrate contamination, manure holding ponds should be lined to prevent the infiltration of rain-leached nitrates into the ground water.

CHAPTER 8. PROPOSED GROUND WATER DATA COLLECTION PROGRAMS

Additional data on ground water are needed to both refine estimates of the total water in storage and to define more precisely the hydrology of the Petaluma Valley ground water basin so that the ground water resources can be managed prudently.

Determination of Ground Water Levels

To accurately evaluate the ground water potential of an area, a wide areal distribution of ground water level data gathered over a long period of time is necessary. This information can be used to determine the overall condition of the basin and to define areas of intense, increasing, or decreasing ground water pumpage. Ground water level data can also be used to evaluate the effects of geologic structures, such as faults and geologic formations, on the movement and occurrence of ground water. Ground water level maps constructed from these data permit a more accurate estimate of total ground water in storage.

At present, 12 wells in the Petaluma Valley study area are being monitored by DWR. A new network is being implemented consisting of 4 of the presently monitored wells and existing wells at 25 additional locations (Figure 17). The 25 additional locations were selected on the basis of geology, hydrology, existence of a well at that location, and information on the construction of the well. Construction data are available for the additional wells; these data are vital in determining the zone from which ground water is being extracted. Presently monitored wells lacking these data have been dropped from the proposed network.

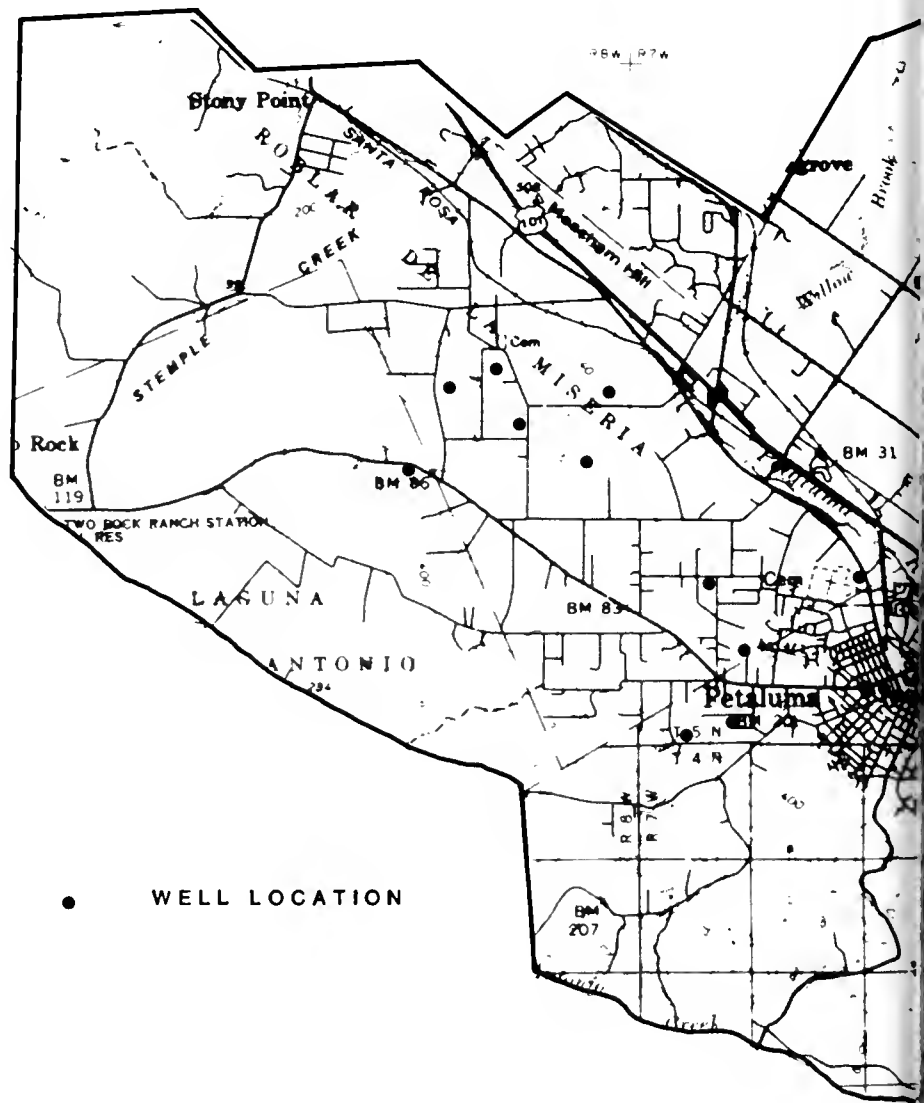
Wells added at the additional locations tap a single aquifer or zone, and

therefore represent the water level of this ground water body alone. A few "deep composite" wells have been selected for areas where no other wells are available; construction data is available for these wells, which tap ground water from several aquifers or zones. Water levels in deep composite wells can be correlated with water levels in other wells of similar depth and construction (gravel packed or multiple perforations) to determine the effects of faults and other barriers on the movement of ground water.

After several years of measurement, data from the new network should be analyzed to better define basin hydrology, including the role of faults in ground water movement and the extent of aquifer continuity. After sufficient ground water level data have been collected to verify estimates of total ground water in storage, the monitoring network should be reevaluated. Those wells whose data are no longer necessary should be dropped.

Determination of Annual Amount of Ground Water Recharge

The amount of water that can be extracted annually from a ground water basin without causing adverse effects is the sustained yield of that basin; it generally equals the average volume of water recharged annually. Recharge in the Petaluma Valley is the result of rain falling on recharge areas because, with the exception of the Petaluma River, streams do not flow across recharge areas (Figure 7). Recharge from rainfall equals the total rainfall minus runoff and evapotranspiration, and varies from year to year. Recharge is greatest on flat, permeable soils, which allow greater infiltration. At present, data are insufficient to allow accurate estimates of average annual recharge in the



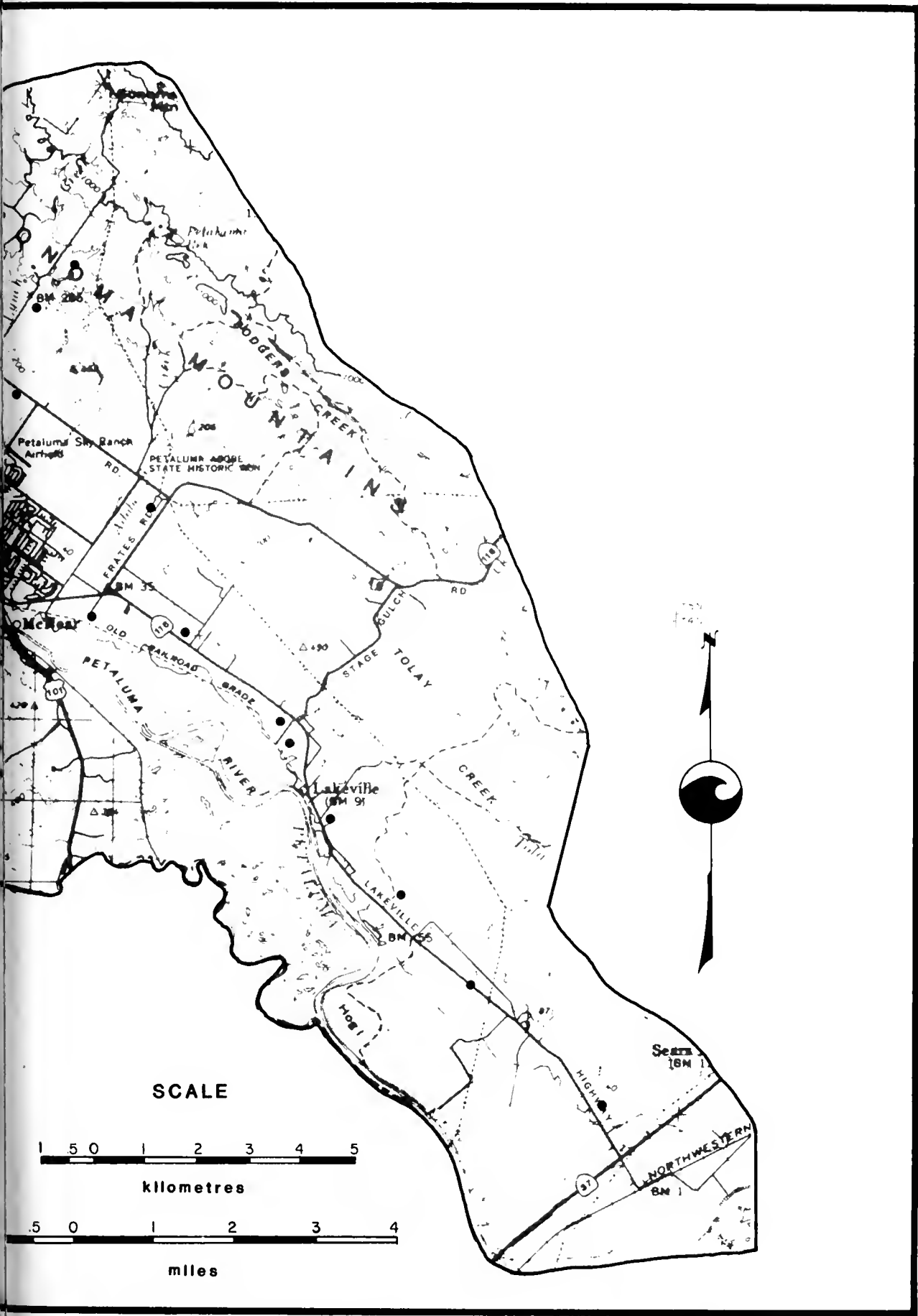
● WELL LOCATION

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
CENTRAL DISTRICT

PETALUMA VALLEY SONOMA COUNTY GROUND WATER STUDY



GROUND WATER LEVEL MONITORING NETWORK



Petaluma Valley to be made. A program to determine the annual amount of recharge would include measurements of rainfall, streamflow, and soil permeability, and estimates of plant evapotranspiration.

Rainfall is measured by the National Weather Service in the City of Petaluma. Neither runoff nor streamflow is presently measured in the Petaluma Valley, although the U. S. Geological Survey maintained gaging stations on the Petaluma River near Petaluma from 1948 to 1965.

Temporary gaging stations on larger streams in the valley would help determine runoff. Reactivating the gaging station on the Petaluma River at Petaluma and adding a temporary gaging station upstream of the recharge areas would measure the reduction in streamflow due to percolation to the ground water body.

Evapotranspiration, while not usually measured directly, can be estimated by measuring evaporation by an accepted method. The volume of water removed by evapotranspiration can then be estimated by comparing the measured rate of evaporation with the rate of evaporation in an area where evapotranspiration is known.

Very general estimates of soil permeability were made by the U. S. Soil Conservation Service for the "Soil Survey of Sonoma County" (Miller, 1972). These estimates can be refined by conducting permeameter tests on each major soil type.

Determination of Changes in Ground Water Quality

Additional ground water quality data are necessary to monitor the extent of sea water intrusion. Data should be collected from shallow wells (less than 60 m, or 200 ft, deep) of known construction. The wells should be within 3 kilometres (2 miles) of the presently known extent of intrusion. Monitoring wells should extract water only from alluvial fan deposits (Plate 1). Water samples from these wells should be analyzed in spring and fall for electrical conductivity. Standard mineral analyses should be taken periodically, such as at 5-year intervals. Changes in ground water quality can be monitored and appropriate corrective measures taken if necessary.

Nitrates are a serious problem in the area northwest of the City of Petaluma, and the nitrate-contaminated water will continue to spread. The study currently being conducted by DWR, Central District (Perkins, in progress) will contain recommendations for continued observation of the nitrate problem. These recommendations should be implemented as soon as possible so that residents will be kept informed about changes in ground water quality and so that any possible mitigating measures can be taken.

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GLOSSARY

Agglomerate. A pyroclastic volcanic rock containing a predominance of rounded to subangular fragments greater than 32 mm in diameter.

Alluvial Fan Deposit. A cone-shaped deposit of alluvium made by a stream where it runs out onto a level plain or meets a slower stream. The fans generally form where streams issue from mountains upon the lowlands.

Alluvium. A geologic term describing beds of sand, gravel, silt, and clay deposited by flowing water during comparatively recent geologic time.

Anion. A negatively charged ion, for example, OH^- or Cl^- .

Anticline. A fold, generally convex upward, whose core contains the older rocks.

Aquifer. A geologic formation that stores, transmits, and yields significant quantities of water to wells and springs.

Aquifer Continuity. Hydraulic interconnection between aquifers so that ground water stored in one aquifer or portion of an aquifer is able to move into another aquifer or portion of an aquifer.

Artesian. An adjective referring to ground water confined under hydrostatic pressure.

Brackish. Water that is intermediate in salt content between streams and sea water; neither fresh nor salty.

Breccia. A rock made up of highly angular, coarse, broken fragments.

Cation. A positively charged ion, for example, H^+ or Ca^{++} .

Chert. A hard, dense siliceous rock of sedimentary origin.

Clay. A term which denotes either (1) particles, regardless of mineral composition, with diameter less than 1/256 mm or (2) a sediment composed primarily of these particles.

Confined. Refers to ground water under sufficient pressure to rise above the aquifer containing it when the aquifer is penetrated by a well. The difference between the water level in a well and the top of the aquifer is the Hydrostatic Pressure. Confined ground water is also known as Artesian.

Conglomerate. A cemented rock containing rounded fragments corresponding in size to gravel. The consolidated equivalent of gravel.

Connate Water. Water entrapped in the openings between particles of a sedimentary rock at the time the rock was deposited. The water may be derived from either ocean water or land water.

GLOSSARY (Continued)

Consolidated. Firm and coherent.

Constant-Rate Pump Test. Test pumping of a water well at a constant rate of discharge while the drop in the ground water level (drawdown) is recorded in the well or a nearby observation well. The drawdown is plotted versus time since pumping began to determine Transmissivity, the rate at which ground water will flow through a unit width of the aquifer.

Contamination. Contamination means an impairment of the quality of the waters of the State by waste to a degree which creates a hazard to the public health through poisoning or through the spread of disease. Contamination includes any equivalent effect resulting from the disposal of waste, whether or not waters of the State are affected.

Continental Deposits. Sedimentary deposits laid down within a general land area and deposited in lakes or streams or by the wind; nonmarine deposits.

Diatomite. An earthy deposit composed of nearly pure silica and consisting of the shells of microscopic plants called diatoms.

Dip. The angle at which a planar feature such as a fault or formation is inclined from the horizontal.

Evapotranspiration (ET). Loss of water from a land area through transpiration of plants and evaporation from the soil.

Fault. A fracture, or fracture zone, along which there has been displacement of the two sides relative to one another. This displacement may be a few centimetres or many kilometres. An Active Fault is one which has had surface displacement within Holocene time (about the last 11,000 years). The inverse of this, that other faults are inactive, is not necessarily true. A Potentially Active Fault is one which shows evidence of displacement during Quaternary time (last 2 to 3 million years).

Fault Plane. The more or less planar surface of a fault along which dislocation has taken place.

Fault Trace. The surface expression of a fault.

Fault Zone. An area along the trace of a large fault consisting of numerous interlacing small faults and/or a confused zone of gouge.

Fold. A bend in rock strata. An Anticline is an upward fold; it influences ground water by inducing flow away from the fold axis. A Syncline is a downward fold; it influences ground water by inducing flow toward the fold axis.

GLOSSARY (Continued)

Formation. A geologic term that designates a specific group of underground beds or strata which have been deposited in sequence one above the other and during a specific period of geologic time.

Fresh Water. Water that is not so affected by sea water intrusion, nitrate pollution, or other water quality problem, as to be detrimental for human use or consumption.

Gouge. Finely abraded material occurring between the walls of a fault, the result of grinding movement.

Gravel. A term which denotes either (1) particles, regardless of mineral composition, with diameter greater than 2 mm or (2) unconsolidated sediment composed primarily of these particles. Gravel frequently is found as lens-shaped units within sandy deposits.

Greenstone. An altered basic igneous rock of greenish color due to the presence of such minerals as chlorite, hornblende, and epidote.

Ground Water Barrier. A body of material which is impermeable or has only low permeability and which occurs below the land surface in such a position that it impedes the horizontal movement of ground water and consequently causes a pronounced difference in the level of the water table on opposite sides of it.

Ground Water Basin. An area underlain by one or more permeable formations capable of furnishing a substantial supply of acceptable quality water. Usually, there is little movement of ground water from one basin to another.

Hydraulic Conductivity. The rate of flow of water in gallons per day through a cross section of one square foot under a unit hydraulic gradient, at the prevailing temperature or adjusted for a temperature of 60°F.

Hydraulics. The aspect of engineering that deals with the flow of water or other liquids.

Hydrograph. A graph showing the changes in the water level in a well with respect to time.

Hydrology. The science that relates to the distribution and circulation of naturally occurring water on and under the earth's surface.

Igneous. Rock formed from the solidification of molten material, either at depth or on the ground surface.

Infiltration. The flow or movement of surface water downward through the soil to become ground water.

GLOSSARY (Continued)

Interbedded. Occurring between beds, or lying in a bed parallel to other beds of a different material.

Intrusive. Igneous rock which cools and solidifies below the earth's surface.

Limestone. A sedimentary rock consisting chiefly of calcium carbonate.

Marine Deposits. Sedimentary deposits laid down on the floor of the ocean.

Mathematical Model. A computer technique which simulates responses of a ground water basin to changes in recharge and pumping patterns. Used as a tool to predict future water levels.

Metamorphic. Rock which has been re-formed in the solid state in response to pronounced changes of temperature, pressure, and/or chemical environment and which takes place below the ground surface. A metamorphic rock originally was of a different form; i.e., it originally was igneous, sedimentary, or a different type of metamorphic rock.

Methemoglobinemia. A bluish or purplish discoloration (as of skin) due to deficient oxygenation of the blood which can be caused by excessive nitrates in drinking water.

Milliequivalent. A contraction of "milliequivalents per million", which is based on molecular weights; the units are "milligram equivalents per kilogram" if derived from data expressed in parts-per-million or "milligram equivalents per litre" if derived from data expressed in milligrams per litre. In analyses expressed in milliequivalents, unit concentrations of all ions are chemically equivalent.

Oxidation. The process of combining with oxygen; rust is a product of oxidation.

Percolation Rate. The rate at which water passes through the fine interstices in earth materials.

Permeability. The ability of a geologic material to transmit fluids such as water. The degree of permeability depends on the size and shape of the pore space and the extent, size, and shape of their interconnections.

Pollution. Pollution means an alteration of the quality of the waters of the State by waste to a degree which unreasonably affects (1) such waters for beneficial uses, or (2) facilities which serve such beneficial uses. Pollution may include contamination.

Potable. Suitable for drinking; said of water and beverages.

Recharge. The processes involved in the absorption and addition of water to the zone of saturation. In this report, natural recharge is recharge that occurs without assistance or enhancement by people; artificial recharge is recharge that occurs when people modify the physical system to increase recharge.

GLOSSARY (Continued)

Reduction. The process of removing oxygen; the opposite of oxidation.

Saline. Consisting of or containing salts (minerals), the most common of which are potassium, sodium, or magnesium in combination with chloride, nitrate, or carbonate.

Sand. A term which denotes either (1) particles with diameter ranging from $1/16$ to 2 mm or (2) a sediment composed primarily of these particles.

Scoria. Material ejected from a volcanic vent. Such material is usually vesicular, dark in color, heavy, and has a partly glassy-partly crystalline texture.

Sedimentary. Said of rocks formed from sediments. Includes such rock types as sandstone, conglomerate, shale, etc.

Serpentinite. A rock consisting almost entirely of the mineral serpentine, which is the alteration product of several types of ultrabasic rocks.

Silt. A term which denotes either (1) particles with diameter ranging from $1/256$ to $1/16$ mm or (2) a sediment composed primarily of these particles.

Soil. A natural body consisting of layers or horizons of mineral and/or organic constituents of variable thicknesses, which differ from the parent material in their morphological, physical, chemical, and mineralogical properties and their biological characteristics.

Sorting. The degree of similarity, in respect to some particular characteristic (frequently size), of the component particles in a mass of material.

Specific Yield. The ratio of the volume of water that a given mass of saturated rock or soil will yield by gravity, to the volume of that mass. This ratio is expressed as a percentage.

Storage Capacity. The volume of space below the land surface that can be used to store ground water. Total Storage Capacity is the total volume of space that could be used to store ground water. Available Storage Capacity is that volume of the total storage capacity that does not presently contain ground water and is therefore available to store recharged water.

Stream Gaging. The process by which the streamflow can be determined by measurement of the water level and velocity in the stream.

Sustained Yield. The volume of ground water that can be extracted annually from a ground water basin without causing adverse effects.

Syncline. A fold in which the core contains the younger rocks; it is generally concave upward.

Thermal Water. Hot or warm water.

Total Dissolved Solids (TDS). The total quantity of minerals (salts) in solution in water, expressed in milligrams per litre.

TRANSCAP. A computer program which determines transmissivity and storage capacity using specific yield data from individual wells. Averaged specific yield data are converted to transmissivities using equations of a curve developed by the DWR investigation of the Livermore and Sunol Valleys (Ford and Hills, 1974). For specific yield values from 3 to 9, the curve is described by the equation:

$$\Delta T = \Delta D \cdot 10 \left[\frac{3.5319 - \frac{7.16288}{|SY| + 0.84}}{|SY| + 0.84} \right]$$

and for specific yield values greater than 9, by the equation:

where $\Delta T = \Delta D \cdot (100 |SY| - 500)$

ΔT = incremental transmissivity

ΔD = incremental depth

$|SY|$ = absolute value for average specific yield for a given interval.

Transmissivity. The rate of flow of water through each vertical strip of aquifer of unit width having a height equal to the saturated thickness of the aquifer and under a unit hydraulic gradient.

Tuff. A rock composed of compacted volcanic fragments smaller than 4 mm in diameter.

Unconformity. A surface of erosion that separates younger strata from older rocks; represents a substantial break or gap in the geologic record.

Water Table. (1) The upper surface of a zone of saturation except where that surface is formed by an impermeable body; (2) The surface of a body of unconfined ground water at which the pressure is equal to that of the atmosphere; (3) colloquially, the surface where ground water is encountered in a well in an unconfined aquifer.

Well Log. A record made by the driller of a water well which lists geologic materials encountered during drilling and information on the construction of the well such as casing perforations and sanitary seal.

Zone of Saturation. A subsurface zone in which all the interstices are filled with water under pressure greater than that of the atmosphere.

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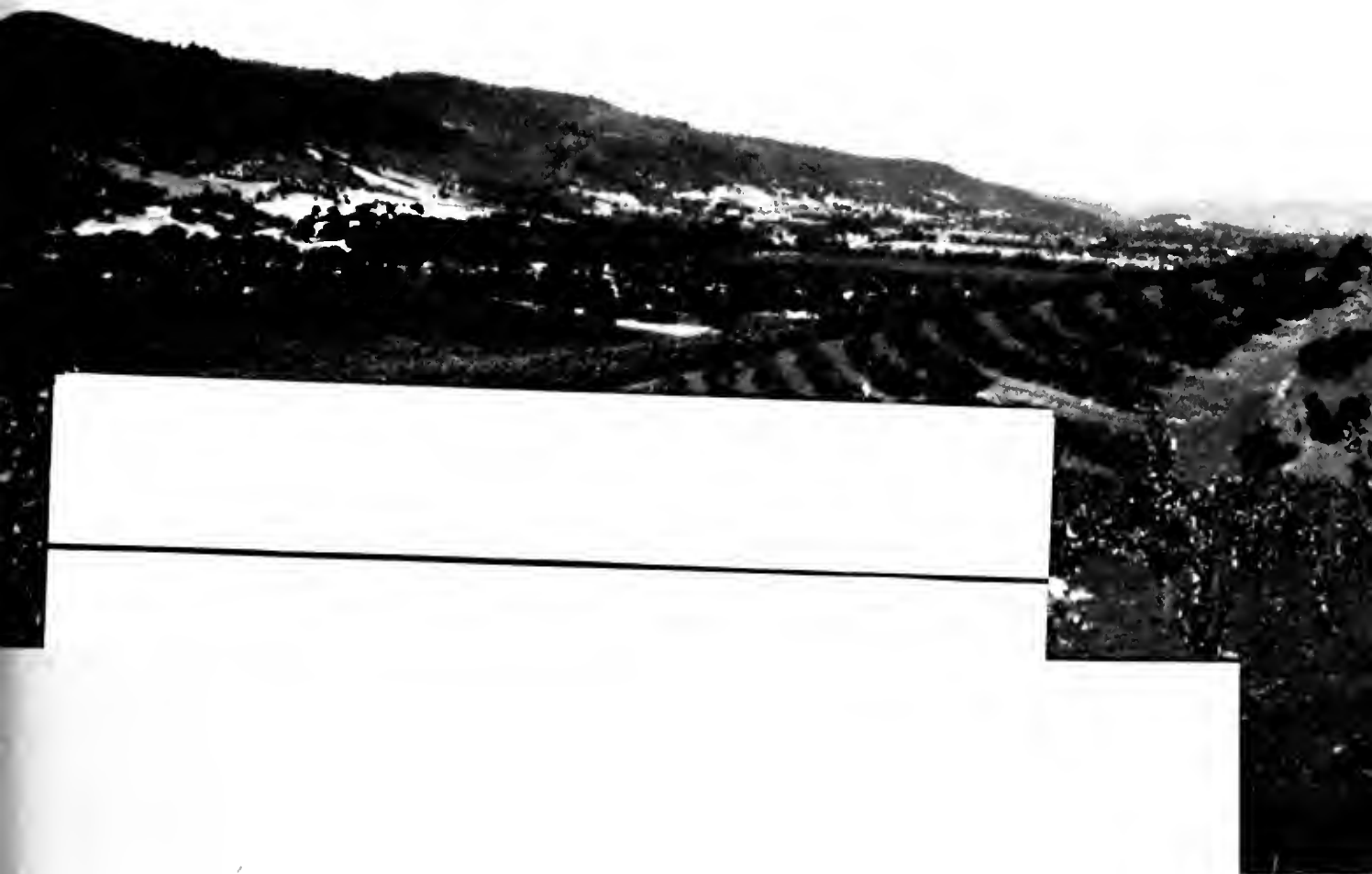
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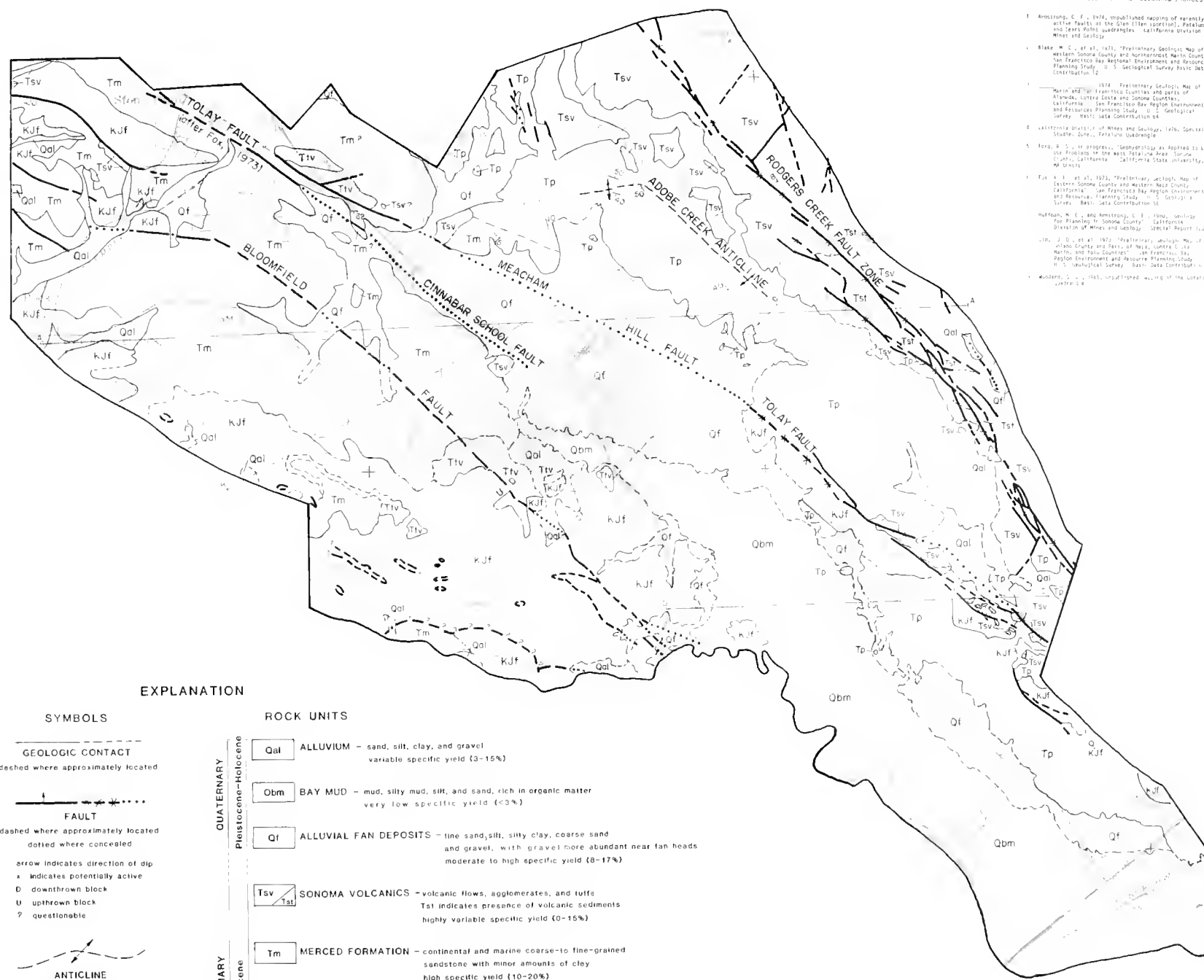
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 9. Woodard, J., 1963, "Unpublished mapping of the Tolay," under 54.

EXPLANATION

SYMBOLS

GEOLOGIC CONTACT
dashed where approximately located

FAULT
dashed where approximately located
dotted where concealed

arrow indicates direction of dip
+ indicates potentially active
D downthrown block
U upthrown block
? questionable

ANTICLINE
showing approximate trace of axial surface

STRIKE AND DIP
of bedding

LINE OF CROSS SECTION

ROCK UNITS

QUATERNARY	Pleistocene-Holocene	Qal	ALLUVIUM - sand, silt, clay, and gravel variable specific yield (3-15%)
		Qbm	BAY MUD - mud, silty mud, silt, and sand, rich in organic matter very low specific yield (<3%)
		Qf	ALLUVIAL FAN DEPOSITS - fine sand, silt, silty clay, coarse sand and gravel, with gravel more abundant near fan heads moderate to high specific yield (8-17%)
TERTIARY	Pliocene	Tsv	SONOMA VOLCANICS - volcanic flows, agglomerates, and tuffs Tst indicates presence of volcanic sediments highly variable specific yield (0-15%)
		Tm	MERCED FORMATION - continental and marine coarse- to fine-grained sandstone with minor amounts of clay high specific yield (10-20%)
		Tp	PETALUMA FORMATION - clay and shale with minor amounts of sandstone low specific yield (3-7%)
		Tiv	TOLAY VOLCANICS - volcanic flows, tuffs, breccias, and agglomerates unknown specific yield, assumed to be very low (<3%)
JURASSIC-CRETACEOUS		KJf	FRANCISCAN COMPLEX - includes chert, sandstone, shale, greenstone, includes fault-bounded, rounded serpentinite bodies apparent specific yield is very low (<3%)

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
CENTRAL DISTRICT

GEOLOGY OF PETALUMA VALLEY SONOMA COUNTY GROUND WATER STUDY

